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AN ANALYSIS OF BAROTROPIC FORECAST ERRORS IN CASES OF RAPID SEA LEVEL CYCLOGENESIS [1]

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ABSTRACT

The 24-hour 500-mb. barotropic forecasts prepared by the Joint Numerical Weather Prediction Unit (JNWPU) have been investigated in 30 cases of rapid sea level cyclogenesis. Composite error maps are presented for the region of cyclogenesis. The 500-mb. errors are found to be significantly larger when the solenoidal field at that level is strong than when it is weak.

1. INTRODUCTION

It is well known that due to the assumption of conservation of absolute vorticity inherent in the barotropic model, it cannot forecast a change in absolute vorticity following the motion (i.e., development) at the 500-mb. level. The purpose of this study is to determine the character of the 500-mb. forecast errors in the vicinity of rapidly deepening sea level cyclones.

There appear to be two classes of cyclogenesis—those in which cyclogenesis at sea level is accompanied by deepening at upper levels, and those in which it is not. In the latter cases, simple superposition of the upper-level trough on a low-level warm tongue results in sea level cyclogenesis, while in the former cases, deepening of the upper-level trough plays the major role in the development of the sea level cyclone. Part of the purpose of this research is to determine whether there are really two distinct classes of cyclogenesis and whether the errors of barotropic forecasts may be anticipated if cyclogenesis is anticipated.

It would seem that if there are two classes of cyclogenesis, the 500-mb. barotropic forecasts may be better for the cases that are initially "quasi-barotropic" at 500 mb. (weak solenoidal field or none at all) than for the cases where the 500-mb. level is baroclinic (strong solenoidal field). This hypothesis is tested in this study.

Although barotropic forecast errors have been analyzed in the past (Staff Members, JNWPU [9, 10]; Cressman and Hubert [4]; Bristor [1]; Gates [5]; Gates et al. [6]) they have not been studied for a *group* of situations where rapid cyclogenesis was occurring over a particular area. (There have been some studies of individual cases; e.g., Charney and Phillips [2], and Charney [3].)

Error fields are constructed relative to the sea level cyclone position at the final time (24 hours after the initial time), and composite maps of the observed and forecast height changes as well as the error fields are presented.

2. DATA AND METHODS OF ANALYSIS

Weather maps on file in the Department of Meteorology and Oceanography at New York University covering the period 1956–1959 were examined to determine when and where cases of rapid cyclogenesis occurred. Rapid cyclogenesis is defined here as a deepening of 20 mb. or more in a 24-hour period. This applies both to a cyclone that has just formed, and to one that already exists but has not yet (previously) deepened the amount required by the above definition. The geographical area for the origin of these

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cases extends from longitude 100° W. eastward to longitude 60° W., and south of 50° N. latitude. These definitions resulted in a selection of 30 cases. The number of cases was limited due to the fact that rapid deepening at the surface is not a very frequent occurrence and that barotropic forecasts have been available for only the past three years. Table 1 gives the dates for the selected cases.

A track for each cyclone center was drawn on a Lambert conformal conic projection with standard parallels at 25.0° N. and 48.5° N. 500-mb. charts for the initial time and for 24 hours after the initial time were plotted and analyzed. (These two time periods will be referred to hereafter as 00 hours and 00+24 hours respectively.) These analyses were checked against the analyses obtained from the National Weather Analysis Center (NAWAC) and any obvious discrepancies were eliminated. A square grid of 196 points was constructed with intersection points 2° of latitude apart as measured on the Lambert conformal projection at the standard parallels. A graphical 24-hour, 500-mb. height change analysis was carried out for each of the 30 cases by placing the center of the grid over the center of the surface cyclone at 00+24 hours. The grid was oriented parallel to the path of the cyclone during the 6 hours ending at 00+24 hours, and the 00 hour and the 00+24-hour maps were superimposed on each other to obtain the graphical height change analysis. The JNWP barotropic forecast was transferred to the Lambert map projection and 24-hour height changes were determined over the same area as the observed changes.

Composite observed and forecast charts were constructed for the 30 cases. In order to determine the height change errors due to the barotropic forecast, the observed composite 500-mb. height change chart was subtracted from the barotropic forecast height change chart. In this manner composite error changes were constructed for the 30 cases.

As noted earlier, the cases occurred during the period 1956 through 1959. During that time three improvements were introduced into the barotropic model: (1) the use of the balance equation (Shuman [8]) beginning on April 20, 1956, (2) enlargement of the grid on October 30, 1957, and (3) elimination during the summer of 1958 of the error due to spurious retrogression of very long atmospheric waves. This latter error probably did not affect the 24-hour barotropic forecasts significantly, especially in the areas under study in this research (Wolff [11]). The effect of the other two improvements will be discussed in section 3.

TABLE 1.—*Dates of cases of rapid cyclogenesis*

Time (GMT)	Date	Time (GMT)	Date
15	February 24–25, 1956	12	November 28–29, 1958
15	November 20–21, 1956	12	December 3–4, 1958
15	March 8–9, 1957	00	December 11–12, 1958
15	April 8–9, 1957	12	December 21–22, 1958
12	June 28–29, 1957	12	January 2–3, 1959
12	November 7–8, 1957	12	January 4–5, 1959
12	November 18–19, 1957	00	January 9–10, 1959
12	November 30–December 1, 1957	00	January 16–17, 1959
12	December 10–11, 1957	12	January 16–17, 1959
12	January 7–8, 1958	12	January 21–22, 1959
12	February 13–14, 1958	12	January 25–26, 1959
12	February 15–16, 1958	12	January 30–31, 1959
12	March 19–20, 1958	12	February 18–19, 1959
12	March 31–April 1, 1958	12	March 12–13, 1959
12	November 17–18, 1958	12	April 14–15, 1959

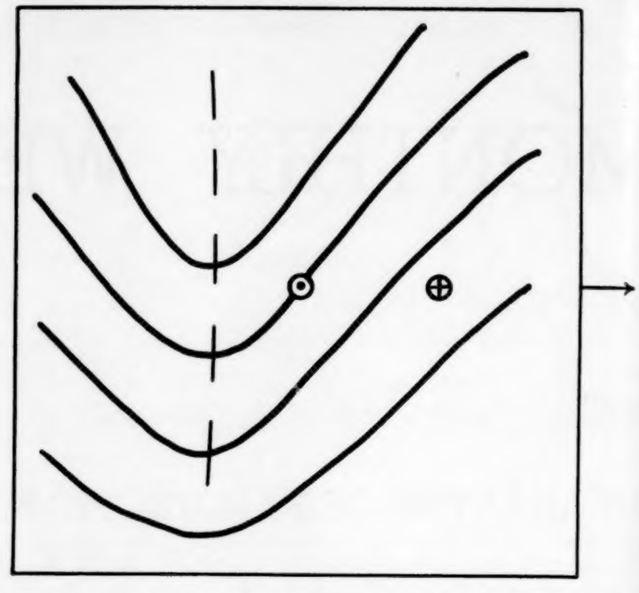


FIGURE 1.—Schematic illustration of method used to determine area in which solenoids at 500 mb. are counted. Circle with cross indicates cyclone center. Arrow is perpendicular to 500-mb. trough line. Circle with dot is center of square.

An effort was made to separate the cases into two groups on the basis of the intensity of the solenoidal field at 00 hours. This was done to test the hypothesis that the barotropic forecast errors may be larger in cases where the atmosphere is initially baroclinic than where it is barotropic.

On a constant pressure chart the number of solenoids is represented by the number of quadrangles formed by isotherms and contours of geopotential height (Saucier [7]). For the purpose of determining the number of solenoids in a given area, 2½° C. isotherms and 100-foot contours were drawn on the NAWAC 500-mb. charts. The following procedure was then used to count solenoids. A square 30° of latitude along each of its sides was constructed. The square was placed on the Lambert map as shown in figure 1, with the 500-mb. trough line parallel to two sides of the square and the cyclone position centered in the right half of the square.

The area obtained from the Lambert conformal projection was then transferred to the NAWAC 500-mb. analysis for each case, and the solenoids were counted. The area is somewhat distorted due to the fact that the NAWAC chart is a polar stereographic projection.

The counting of solenoids did not result in a sharp delineation between the quasi-barotropic and the baroclinic cases. The range of solenoids was from 0 to 77. The 500-mb. level was quasi-barotropic (zero solenoids) in only one of the cases, and therefore the separation of cases was based on the *number* of solenoids. The 30 cases

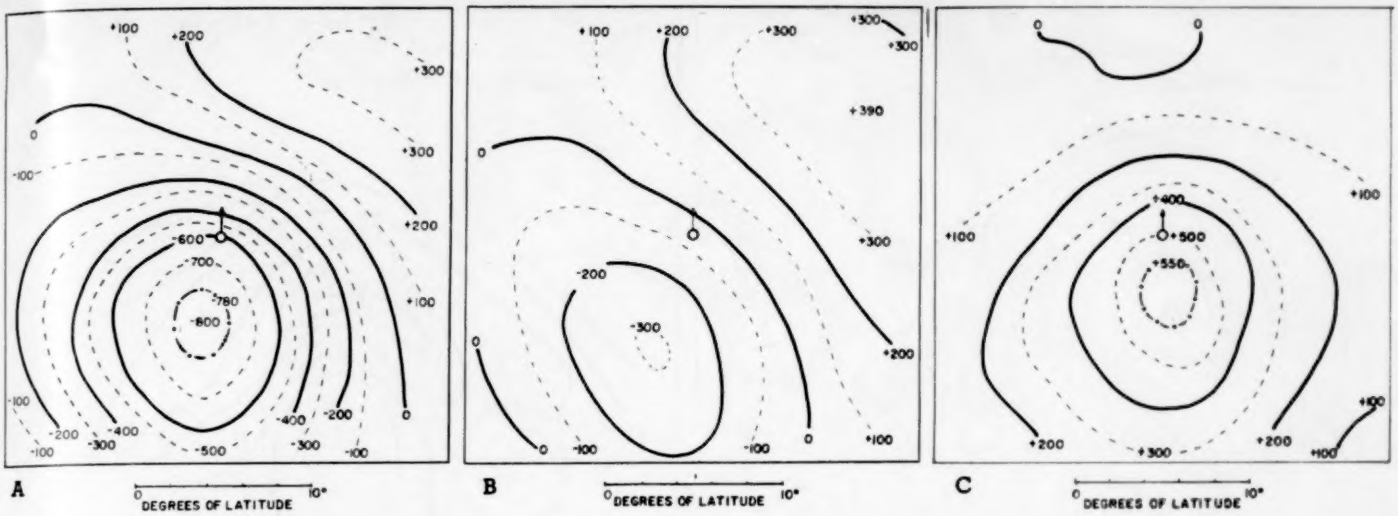


FIGURE 2.—Composite 500-mb. 24-hour height changes and forecast errors (30 cases), (A) observed, (B) barotropically forecast, oriented according to the path of the sea level cyclone center (open circle) during the 6 hours ending at 00+24 hours, (C) composite 500-mb. forecast height change error (forecast minus observed). Units are in geopotential feet (gp. ft.).

were tabulated in order of increasing number of solenoids in order to arrive at an equal number of cases for the "quasi-barotropic" ("weakly baroclinic" would be a more correct description) and the baroclinic cases. (To avoid confusion between "weakly baroclinic" and "baroclinic" cases, the term "quasi-barotropic" (with quotes) will be retained when referring to the "weakly baroclinic" cases.) The median of the 30 cases was used as the separation criterion. This resulted in designating as baroclinic those cases in which the number of solenoids was 20 or greater, and as "quasi-barotropic" those cases having less than 20 solenoids.

Composite 500-mb. observed and forecast height change maps were constructed for the "quasi-barotropic" and baroclinic cases separately.

3. RESULTS

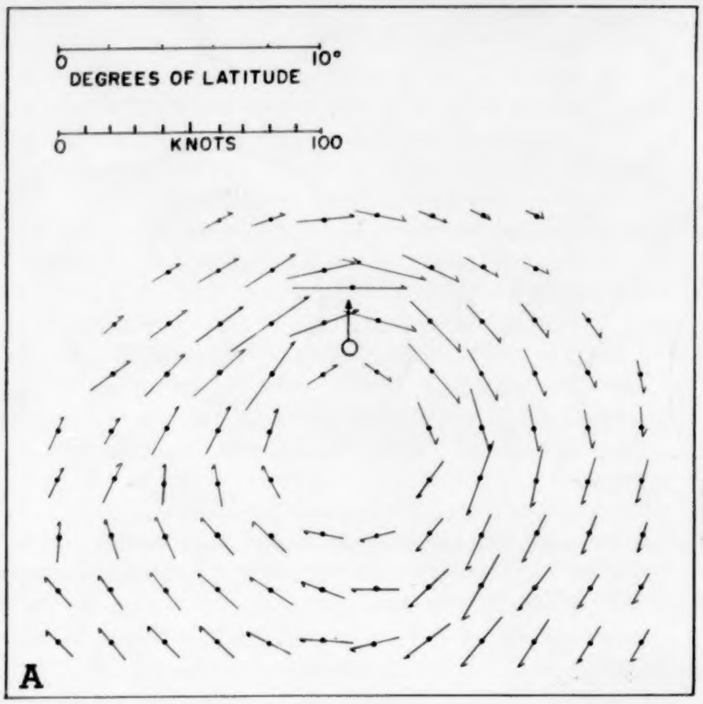
Figure 2A illustrates the pattern of *observed* 24-hour height changes for all 30 cases and figure 2B represents the composite 500-mb. 24-hour height changes from the *barotropic forecasts* for all 30 cases. The center of maximum height decrease is only slightly (about 100 n. mi.) to the left and to the rear of the area on the observed composite chart. The magnitude of the decrease, however, is two and a half times greater on the observed composite.

Figure 2C shows the forecast minus the observed height change, and demonstrates the error field for the 30 cases. The error is in the form of a vortex with the largest error to the rear of the sea level cyclone. This maximum error is of the order of 580 feet. It may be noted that the area covered by an error of 200 feet or greater is roughly circular—about 1200 n. mi. in diameter—and is centered about 150–200 n. mi. to the rear of the surface cyclone. In the area of the grid not affected by the rapidly deepening sea level cyclones the errors are small, implying that the atmosphere is close to being quasi-barotropic.

Perhaps the forecaster involved with barotropic prognostic charts would be aided by some knowledge of the standard deviation of the error over the cyclone center and over the region of largest error. The standard deviation, to the nearest 10 feet, for the four grid points surrounding the cyclone center (representing roughly 60 n. mi. radius around the cyclone) averaged 260 feet. As can be seen in figure 2C the error in this area is about 500 feet. In the region of maximum error represented by the grid points near and within the maximum error contour of 550 feet, the average standard deviation was only 200 feet.

It might be argued that the large composite error could be due to randomness. Therefore, the significance of the error was tested using the Student's "t" test on the grid points comprising the two areas mentioned above. The error was found to be significant at less than the 1 percent level; i.e., very significant in these areas.

Composite observed, barotropic forecast, and error charts (not shown) were constructed for the 25 cases after the balance equation was introduced and the grid was enlarged. These showed that there was little difference in the error field from that of the composite error chart for the 30 cases (the composite errors for the 25 cases were actually somewhat larger). The fact that the elimination of the five cases before the improvements were used operationally in the model did not result in better forecasts is not really surprising. The use of balanced winds successfully suppresses spurious anticyclogenesis, but would not be expected to improve the barotropic forecasts in the region to the rear of rapidly deepening sea level cyclones. As far as enlargement of the grid is concerned, this has served to produce better barotropic forecasts (Staff Members, JNWPU [9,10]) but apparently none of the five cases



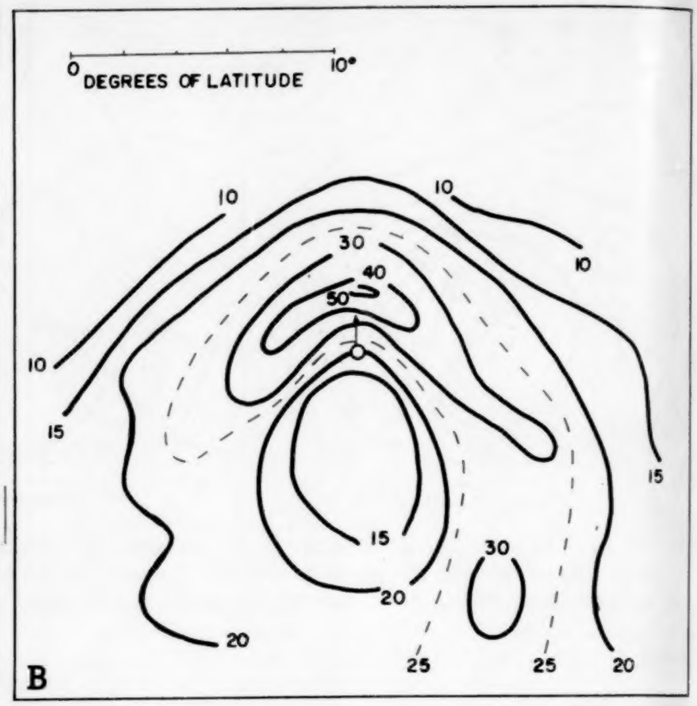


FIGURE 3.—(A) Composite vector wind error of the geostrophic wind (30 cases). (B) Analysis of magnitudes of vectors in (A) oriented same as figure 2.

in this study before the enlargement was sufficiently close to the boundaries of the grid to be affected by errors due to the boundary conditions imposed. Using the result that the improvements introduced in the barotropic model failed to make any real difference in the errors found in the region of cyclogenesis, the analysis of the errors and the conclusions drawn from this analysis will be based on all 30 cases.

500-mb. barotropic forecast error of the geostrophic wind.—The error in the geostropic wind is determined from the gradient of the height errors and may be obtained by applying a geostropic wind scale to the contours of the height errors.

Figure 3A illustrates the magnitude of the error for points around the cyclone center. In the portion of the figure that is devoid of errors the error of the geostrophic wind was less than 10 knots. The direction of the vectors shows the error field to be an anticyclone vortex, meaning that the cyclonic vortex was underforecast. This follows from the definition of the composite 500-mb. height error adopted in this paper, i.e., forecast minus observed equals error.

In figure 3B is shown the analysis of the vector magnitudes from figure 3A. Whereas the largest height error is to the rear of the sea level low center, the largest geostrophic wind error is about 100–150 n. mi. ahead of the sea level low center and is of the order of 50 knots. In general, as figure 3B indicates, the semicircle to the right of the sea level cyclone path has a somewhat greater wind error than that to the left of the cyclone center. The area covered by an error of 25 knots or greater is surrounded by the dashed line in figure 3B, and is rather extensive.

Baroclinic vs "quasi-barotropic" composites.—Figures 4 and 5 represent the observed and forecast 24-hour 500-mb. height changes and the error charts (forecast minus observed) for the 15 baroclinic and 15 "quasi-barotropic" cases respectively. In comparing the two observed height change charts, one notes that the 15 "quasi-barotropic" cases show an average height decrease that is about 200 feet less in absolute magnitude than that of the baroclinic cases. Other differences apparent in the observed height change charts for the two types of cases are: (1) the maximum height decrease is found closer to the sea level cyclone center on the composite for the "quasi-barotropic" cases, and (2) the −500-foot height change contour is found in the same approximate location on all sides of the cyclone center in both types of cases except to the rear, where the −500-foot contour extends about 250 n. mi. farther to the rear of the storm in the baroclinic cases. The forecast composite charts for the two types of cases (figs. 4B and 5B) are seen to be alike.

The maximum error for the "quasi-barotropic" cases (fig. 5C) is about 150 feet smaller in absolute magnitude than that for the baroclinic cases (fig. 4C), but it is concentrated over a smaller area. This maximum error (for the "quasi-barotropic" cases) lies about 250 n. mi. closer to the cyclone center, and it is directly to the rear of it in both cases.

A chart showing the difference between the two error charts is presented in figure 6. It is seen then that the average difference in the vicinity of the cylcone center is almost negligible. The maximum difference is centered about 500 n. mi. to the rear of the surface low center. The dashed line in figure 6 represents the 400-foot error

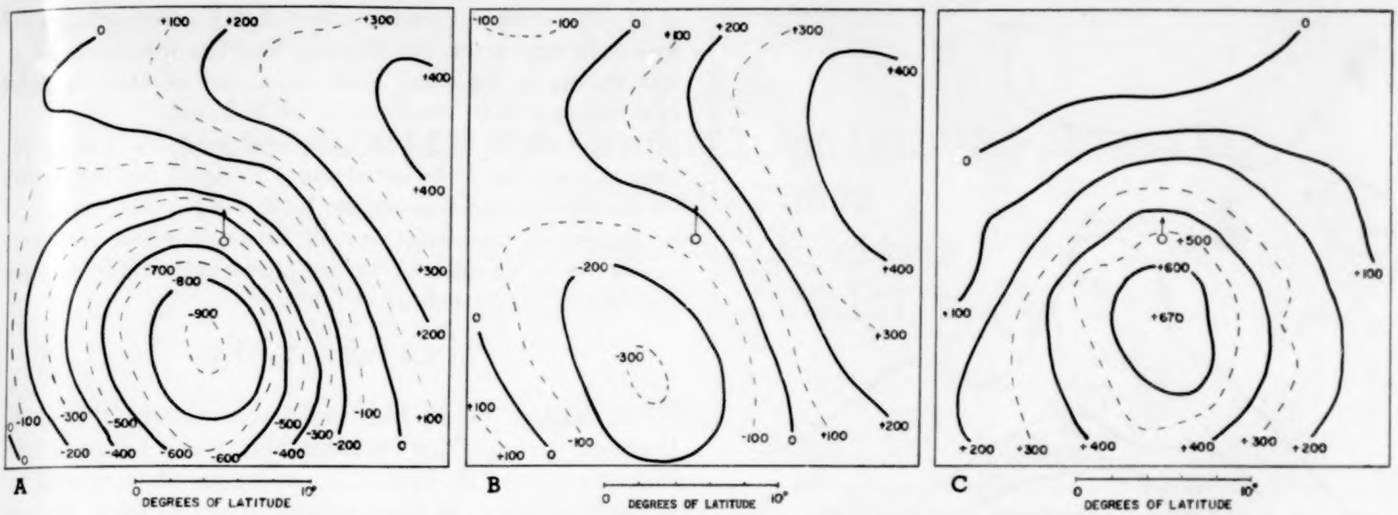


Figure 4.—Composite 500-mb. 24-hour height changes (15 baroclinic cases), (A) observed, (B) barotropically forecast, (C) composite 500-mb. height change error (forecast minus observed). Oriented same as figure 2. (Units in gp. ft.).

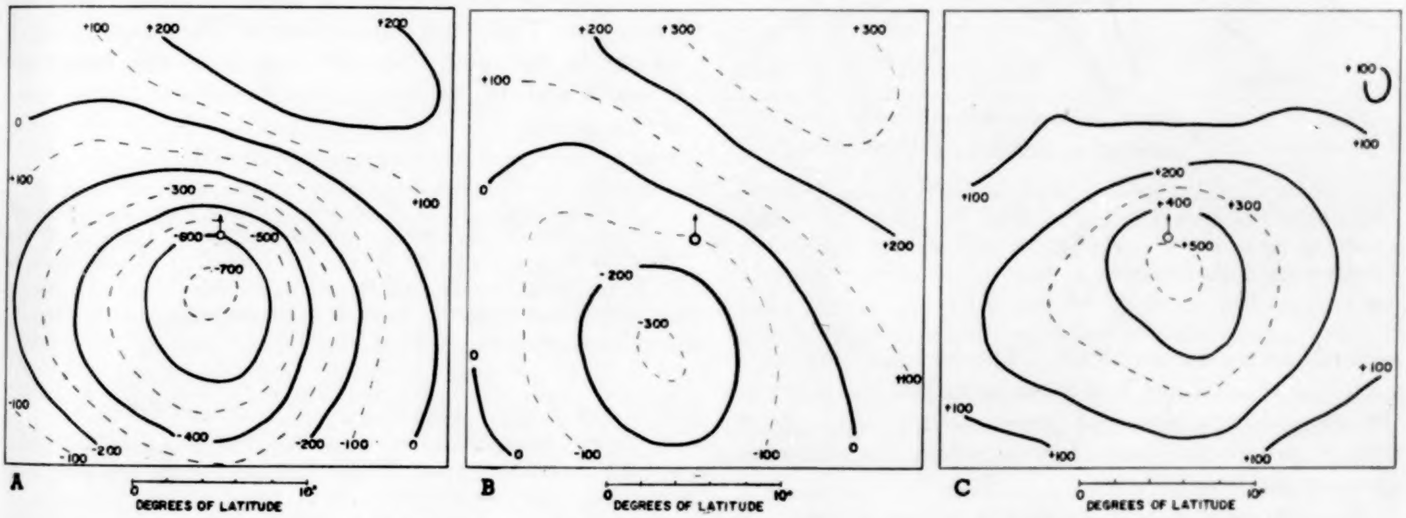


Figure 5.—Same as for figure 4 but for 15 "quasi-barotropic" cases. (Units in gp. ft.).

contour on the composite error chart for the 30 cases (fig. 2C). At the grid points lying within this area the Student's "t" test was applied to determine whether the difference between the forecasts was statistically significant. Of those tested, the seven grid points surrounded by the dot-dash line were found to be significant at the 5 percent level. This area is approximately a circle roughly 350 n. mi. in diameter. Four of the seven grid points were significant at the 2 percent level and two points were significant at the 1 percent level. These two points are indicated with checks on the figure.

In view of the fact that the composite barotropic forecasts are similar for both the "quasi-barotropic" and baroclinic cases, it is obvious that the difference in the composite observed height change charts for the two types of cases accounts for the difference in the composite height change error charts. The apparent inference here is that there are significant differences between the two types of cases over a relatively small part of the area covered by the grid. It must be kept in mind, however, that the separation of cases into the two types was not as sharp as one would have desired.

4. SUMMARY AND CONCLUSIONS

The composite height change charts for the 30 cases of cyclogenesis studied indicate that the barotropic forecasts predicted the area of maximum height decrease in approximately the right location, but the magnitude of the maximum decrease was observed to be two and a half times greater than forecast. The entire area of decrease was larger than forecast. This was due to the failure of the barotropic forecasts to predict the deepening of the trough.

The composite error chart for the 30 cases shows the error to be in the shape of a circular vortex and the maximum error to be of the order of 550–600 feet. It appears that the barotropic forecast error at 500 mb. represents a failure to forecast the development of a

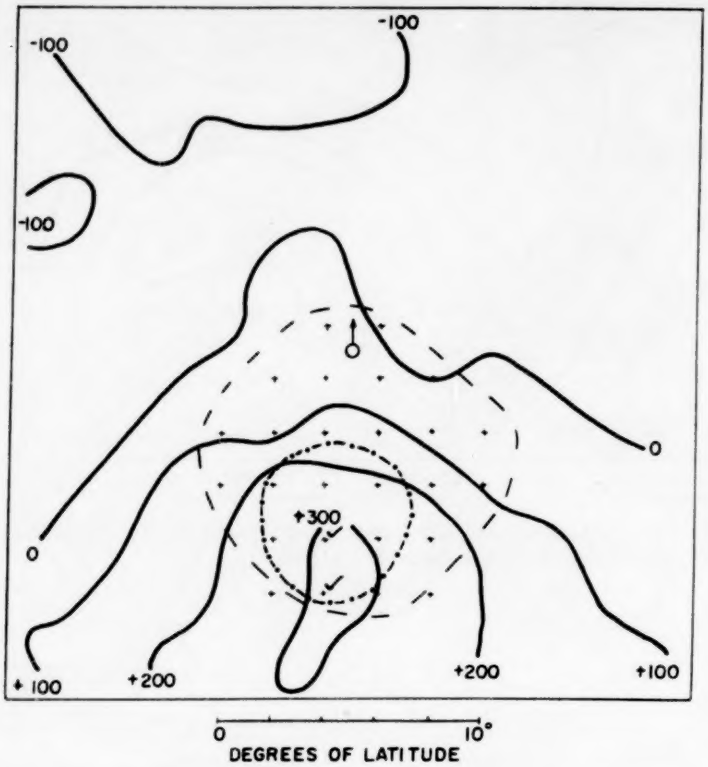


FIGURE 6.—Composite 500-mb. baroclinic height change error minus composite "quasi-barotropic" height change error. Oriented same as figure 2. (Units in gp. ft.) (See text for explanation of broken and dash-dot lines.)

cyclonic vortex at that level. The superposition of this vortex on the 500-mb. flow pattern distorts the latter into the shape of the observed pronounced trough. At the surface, where the basic flow is weak, the superposed vortex appears as a cyclone.

The composite observed 500-mb. height change chart for the "quasi-barotropic" cases shows both the magnitude and the area of the height changes to be smaller than for the baroclinic cases. The barotropic forecasts are similar for both types of cases. The composite error charts for the baroclinic and "quasi-barotropic" cases, therefore, show essentially the differences in the observed composite height change charts.

A chart showing the difference between the two types of cases indicated that the difference was statistically significant in a region to the rear of the sea level cyclone center.

The results presented above do not clearly resolve the question of whether there are really two distinct classes of cyclogenesis. The composite of cases studied indicates that although there is a region in the area of cyclogenesis where the error for the "quasi-barotropic" cases is significantly less than that for the baroclinic cases, the error charts for the "quasi-barotropic" cases themselves contain a large positive error. This implies that the rapid deepening of a surface cyclone may be independent of the degree of baroclinicity at 500 mb.

The barotropic forecast error of the geostrophic wind was determined for the 30 cases and the maximum error was found to lie some distance ahead of the sea level cyclone, and to be of the order of 50 knots.

On the whole, in the 30 cases examined, the barotropic forecasts appear to be satisfactory in areas not influenced by deepening cyclones at sea level. They are, as might be expected, unsatisfactory in areas of rapid sea level cyclogenesis whether the atmosphere be initially "quasi-barotropic" or baroclinic at 500 mb.

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MEASUREMENT OF SENSIBLE AIR-GROUND INTERFACE TEMPERATURES

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ABSTRACT

Several methods of measuring the sensible air-ground interface temperature are discussed. The sensible air-ground interface temperature is here defined as that temperature of the interface as indicated by properly exposed temperature sensors. A comparison is made between the temperature of a copper plate in direct contact with the soil surface, and that indicated by the bottom plate of a "Suomi-Kuhn Economical Net Radiometer" at night. Results using several types of temperature sensors are discussed. Temperatures obtained from a copper plate with a thermohm sensor and the lower plate of a modified net radiometer show an average difference of 0.3° C.

1. INTRODUCTION

It is axiomatic that changes in the temperature of the air near the ground are influenced directly by changes in the temperature of the ground surface. Most of the methods commonly used in minimum temperature forecasting either ignore soil temperatures completely [1], assume that the parameters in a given location are constant [2], or use values obtained from published tables without considering local variations [3].

Soil composition, density, moisture content, etc., vary with time and space. These variables determine the thermal characteristics of a given parcel of soil, and hence are major contributing factors to the radiative temperature of the soil surface. The need for continuous measurements of soil parameters is obvious.

Measurement of the true air-soil interface temperature is a very difficult thing, because it is almost impossible to locate a sensor at the true interface, and because of the large spatial fluctuations of the parameter. If one can measure the sensible air-ground interface temperature at a given spot, fluctuations of this value will be a good index of the over-all variability in the given area. This is the premise for the following work.

2. METHODS OF MEASURING SENSIBLE TEMPERATURE OF AIR-GROUND INTERFACE

One of two methods is usually used to determine the surface temperature. The most common is to lay either an alcohol-in-glass or a mercury-in-glass thermometer on the surface [4] and assume that the indicated temperature is the desired value. This technique has several disadvantages: (1) The bulb of the thermometer, if laid on the soil, is radically affected by wind. (2) The glass bulb of the thermometer is subject to marked "greenhouse effect" (radiative heating during incoming radiation periods and radiative cooling during outgoing radiation periods). (3) If the thermometer is partially buried, it gives a mean temperature of the upper layers of soil depending upon the depth to which the bulb is buried. (4) It requires manual reading and does not permit obtaining a continuous record. (5) Dirt carried by wind will bank around the thermometer bulb resulting in a continuous change of the depth of the bulb in the soil.

The second technique is to lay a fine wire thermocouple on the ground surface [5]. This method eliminates many of the radiative effects, but is subject to cooling and warming by the wind when direct contact with the soil is not maintained. The thermocouple is also affected greatly by drifting soils.

The device described below was designed in an attempt to minimize the above effects, and also to enable continuous recording of fluctuations in the temperature. It is not believed that this device will determine values to within tenths of a degree, but the accuracy is of the same order of magnitude as that of other parameters used in the temperature forecast studies being conducted by the authors.

A copper plate 3 x 4 inches in area and about 0.05 inch thick was made containing an enclosure for the sensing element (see fig. 1). Copper was chosen because it has about the highest conductivity of the cheaper metals and also because, as it oxidizes, the surface becomes similar in color to that of moist soil. A thinner sheet of copper was used in earlier tests, but it tended to buckle and would not maintain good contact with the ground. The copper plate was laid on top of barren soil with the lower surface in firm contact with the soil and the upper surface subject to the same effects of wind, radiation, and moisture as the

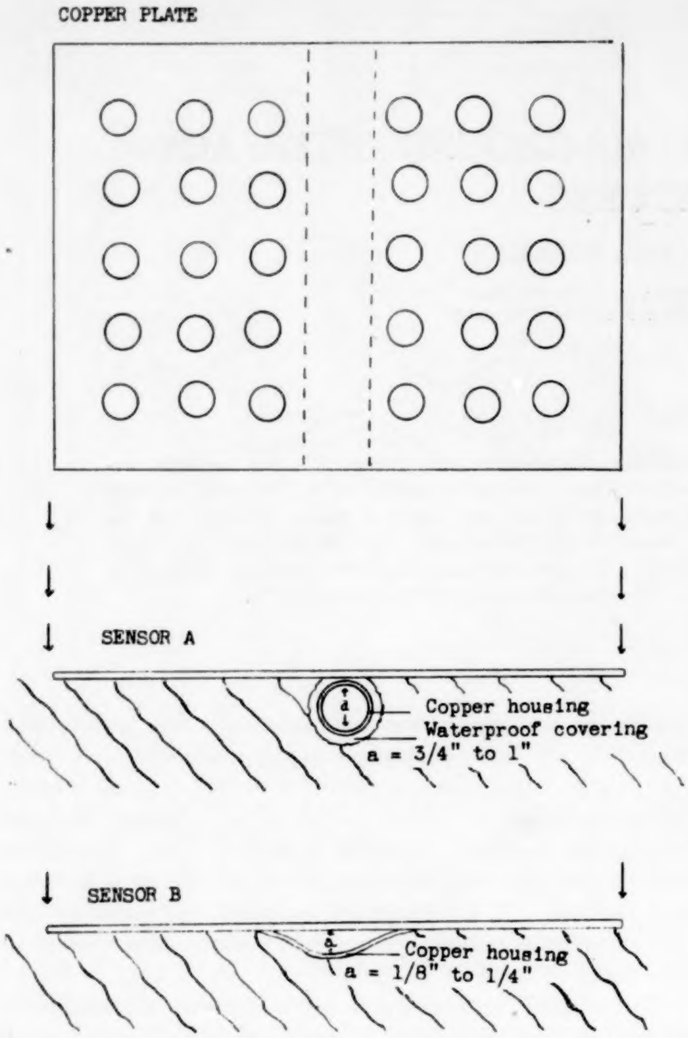

FIGURE 1.—Diagram showing copper plate with holes bored at ½-inch intervals, and arrangement of three types of temperature-sensing elements when plate was placed in contact with soil. Sensor A: soil thermograph; Sensor B: thermistor or small thermohm.

surrounding soil surface. To prevent the plate acting as a water shield to precipitation or a hindrance to evaporation of soil moisture, ¼-inch holes were drilled at ½-inch intervals over the entire surface. Three types of temperature sensors were tested in the plates.

A small copper plate with a mercury thermometer as a sensor was used by Ramanathan [6] as a device to measure surface temperatures. Geiger [5] considers this the best way to use a mercury thermometer to measure ground temperatures.

MODIFIED SOIL THERMOGRAPH

The first sensor tested was a Gotham Instrument Company soil thermograph using a gas-filled Bourdon-tube sensor. The sensing element in this instrument is about ¾ inch in diameter and therefore it was found necessary to try to insulate the bulb enclosure on the plate from the ground, allowing only the wings of the plate to lie in direct contact with the ground. Seven or eight thicknesses of asbestos were glued to the lower part of the enclosure (fig. 1A), and this was then painted with a waterproof white paint. Continuous testing of this modified soil thermograph over a period of 2 years has shown satisfactory results. Occasional checks on the accuracy of the sensing element have been made by inserting the bulb of a mercury-in-glass thermometer under the edge of the copper plate.

THERMISTOR SENSOR

The second sensor tested with the copper plate was a No. 419 coated Air Force radiosonde thermistor. The thermistor was inserted in a piece of polyethylene tubing to insure a moisture-resistant seal. The tubing with the enclosed thermistor was then sealed in the copper housing with a water-resistant plastic sealer. The small size of the thermistor enabled the use of a plate which lay nearly flat on the ground over the entire surface with only a slight indentation in the soil of ⅛ to ¼ inch (fig. 1B).

THERMOHM SENSOR

The third sensor tested was a ¼-inch diameter thermohm used with a six-point Bristol recorder. The thermohm sensor was sealed in the copper housing with the plastic sealer. The plate was the same as in figure 1B, but with an indentation in the soil surface of about ⅜ inch.

USE OF NET RADIOMETER FOR INTERFACE TEMPERATURE MEASUREMENT

A completely different technique for measuring the sensible soil-surface temperature was used as a check on the soil plate measurements. Temperatures indicated by the bottom plate of a Suomi-Kuhn Economical Net Radiometer [7], which was mounted about 3 feet above the ground, were used as an indication of the sensible soil-surface temperatures at night. A modification of the Suomi-Kuhn net radiometer was constructed using a piece of styrofoam for the housing and Saran Wrap for the plastic covers. It was found that these modifications made possible longer exposures of the instrument to the weather. The tendency of moisture to accumulate between the two plastic covers of the net radiometer was not nearly as marked in the modified instrument. It was possible to leave the instrument exposed for as much as 3 weeks to the winter weather, including some snows, without changing the Saran Wrap covers. Use of the polyethylene covers required changing nearly every day because of dew and frost deposits. Comparison of the readings obtained from the two instruments showed that the net radiation data recorded by each instrument were almost identical when using thermistors as sensors.

3. COMPARISON OF METHODS

A comparison of the three methods of measuring the

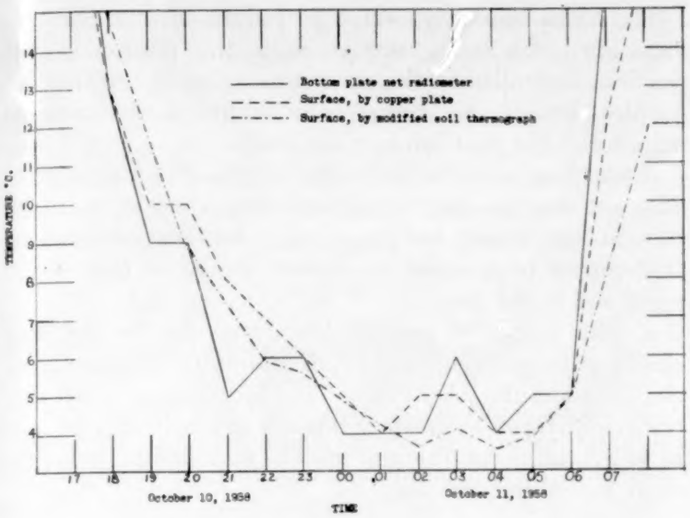

Figure 2.—Comparison of "sensible soil-surface temperature" of dry soil as recorded by bottom plate of "Suomi-Kuhn Economical Net Radiometer", a copper plate with thermistor sensor, and the modified soil thermograph.

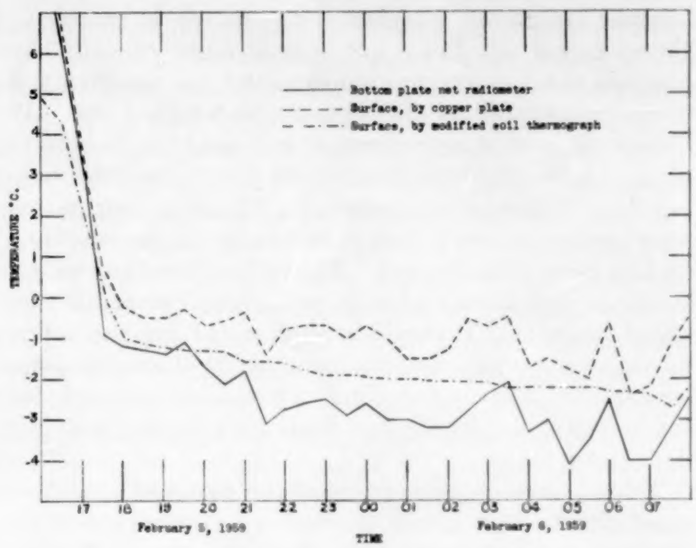

Figure 3.—Comparison of "sensible soil-surface temperature" of moist soil as recorded by bottom plate of a "Suomi-Kuhn Economical Net Radiometer", a copper plate with thermistor sensor, and the modified soil thermograph.

Table 1.—*Hourly comparison during nighttime hours of "sensible soil-surface temperature" (°C.) as recorded by the bottom plate of a modified "Suomi-Kuhn Economical Net Radiometer" and a copper plate using a ¼-inch thermohm sensor, over a period of 1 week*

Sensor Type	Time														
	p.m.						a.m.								
	6	7	8	9	10	11	0	1	2	3	4	5	6	7	8
								November 29, 1959							
Soil Plate								−4.9	−5.1	−5.6	−6.0	−6.1	−6.0	−6.0	−5.5
Net Radiometer								−4.3	−5.1	−5.6	−7.2	−7.4	−6.7	−6.4	−6.5
Difference								−0.6	0	0	+1.2	+1.3	+0.7	+0.4	+1.0
								November 29-30, 1959							
Soil Plate	0.4	−1.0	−1.9	−2.8	−3.4	−3.9	−4.1	−4.0	−3.9	−3.2	−2.4	−3.0	−4.0	−4.5	−3.4
Net Radiometer	0.4	−2.2	−2.5	−2.7	−3.4	−4.3	−4.0	−4.3	−4.5	−4.1	−3.2	−2.3	−3.5	−5.2	−3.3
Difference	0	+1.2	+0.6	−0.1	0	+0.4	+0.1	+0.3	+0.6	+0.9	+0.8	−0.7	−0.5	+0.7	+0.1
								November 30–Dec. 1, 1959							
Soil Plate	1.6	0.2	−0.9	−1.7	−2.2	−2.6	−2.9	−3.5	−3.7	−4.0	−4.2	−4.4	−5.3	−4.5	−4.3
Net Radiometer	1.8	−1.2	−1.2	−2.5	−2.1	−3.3	−2.4	−3.8	−3.7	−3.6	−5.5	−4.6	−5.4	−4.3	−4.2
Difference	−0.2	+1.4	+0.3	−0.8	−0.1	−0.7	−0.5	+0.3	0	−0.4	+1.3	+0.2	+0.1	−0.2	−0.1
								December 1-2, 1959							
Soil Plate	1.0	0	−1.2	−1.7	−1.1	−2.1	−2.4	−3.2	−3.9	−4.0	−4.0	−4.5	−4.8	−4.5	−3.9
Net Radiometer	−0.2	−0.9	−1.3	−2.0	−1.3	−1.1	−1.7	−3.9	−4.5	−4.9	−4.5	−5.4	−5.9	−5.1	−4.7
Difference	+1.2	+0.9	+0.1	+0.3	+0.2	−1.0	−0.7	+0.7	+0.6	+0.9	+0.5	+0.9	+0.9	+0.6	+0.8
								December 2-3, 1959							
Soil Plate	1.2	0	−0.9	−1.3	−2.2	−3.0	−3.0	−3.8	−4.2	−4.5	−4.5	−5.0	−5.0	−5.2	−4.5
Net Radiometer	0.8	−0.9	−1.1	−2.0	−3.1	−3.7	−3.0	−4.1	−5.5	−5.8	−5.0	−5.3	−5.2	−4.3	−5.1
Difference	+0.4	+0.9	+0.2	+0.7	+0.9	+0.7	0	+0.3	+0.7	+1.3	+0.5	+0.3	+0.2	−0.9	+0.6
								December 3-4, 1959							
Soil Plate	0	−1.3	−2.8	−3.6	−4.0	−5.0	−5.5	−5.8	−6.3	−6.7	−7.0	−7.8	−7.2	−8.3	−7.4
Net Radiometer	−0.2	−1.3	−3.5	−4.3	−3.7	−4.5	−6.3	−4.9	−5.8	−6.6	−6.7	−8.3	.....	−8.6	−7.8
Difference	+0.2	0	+0.7	+0.7	−0.3	−0.5	+0.8	−0.9	−0.5	−0.1	−0.3	+0.5	.....	+0.3	+0.4
								December 4-5, 1959							
Soil Plate	−3.0	−4.0	−5.0	−6.0	−5.3	−7.1	−7.9	−7.5	−8.2	−8.4	−9.0	−9.0	−9.2	−9.3	−7.7
Net Radiometer	−2.8	−3.5	−5.0	−5.1	−6.3	−7.9	−8.2	−8.3	−9.0	−9.3	−10.1	−9.6	−9.5	−9.7	−7.7
Difference	−0.2	−0.5	0	−0.9	+1.0	+0.8	+0.3	+0.8	+0.8	+0.9	+1.1	+0.6	+0.3	+0.4	0
								December 5, 1959							
Soil Plate	−3.0	−1.5	−4.9	−5.8	−6.0	−6.2	−6.4								
Net Radiometer	−4.1	−2.2	−5.0	−6.2	−6.6	−7.2	−7.4								
Difference	+1.1	+0.7	+0.1	+0.4	+0.6	+1.0	+1.0								

Average difference +0.32° C.
Extreme differences +1.4° and −1.0° C.

sensible air-ground interface temperature is shown in figures 2 and 3. These are typical night runs. They compare the temperature indicated by the modified soil thermograph and by the copper plate with a No. 419 thermistor, with the temperature indicated by the bottom plate of a Suomi-Kuhn Economical Net Radiometer having No. 419 thermistors as sensors. The three instruments were exposed within 10 feet of each other in the center of a 50-foot circle of barren soil. The soil had been cultivated, sterilized with arsenic trioxide, and allowed to weather for about 5 months. It should be emphasized that the instruments were not sampling the same parcel of soil, but similar parcels. The data for figure 2 were obtained while the soil was dry, and for figure 3 while the soil was moist but not saturated.

Table 1 shows a comparison of the data obtained from a soil plate with a ¼-inch thermohm as a sensor, and the modified net radiometer using No. 405 Brown Weather Bureau radiosonde thermistors as sensors. The net radiometer was mounted directly above the soil plate in order to sample as nearly as possible the same parcel of soil surface. A continuous record was obtained on separate recorders during the week of November 29 through December 5, 1959. To reduce the possibility of bias, the data from each recorder were read off and recorded by different people on separate sheets of paper. These were then combined as shown in the table. Data for nighttime hours only were used since the bottom plate of the net radiometer is subject to effects of reflected short-wave radiation during daylight hours. Visual checking during this period showed no signs of moisture condensing between the Saran Wrap covers and no dew formation.

4. SOURCES OF ERROR

SOIL PLATE

In the discussion of possible errors which might be introduced into the measurement of the "sensible air-soil interface temperature" by means of the copper plate technique, errors peculiar to particular sensors are not discussed since this information is well covered in the literature.

A first source of error involves the diameter of the temperature sensor. As has been pointed out by Geiger [5], "in order to understand the heat economy of the earth it is necessary to know the temperature of the surface itself." In determining the sensible air-ground interface temperature, the smaller the diameter of the sensor the more nearly the copper plate can be constructed as a flat surface which will lie in direct contact with the surface of the ground.

A second factor which influences the accuracy of the measurement is the penetration of moisture into the sensor enclosure. It is important to make a waterproof seal around the sensor since in saturated conditions the sensor is effectively immersed in water and errors are introduced.

The third source of error is failure of the plate to maintain continuous contact with the ground. This problem is similar to that encountered with the thermocouples, but if the copper is of sufficient thickness to remain flat the problem is minimized.

A fourth source of error is the fact that the copper plate does not change color as the soil does when its moisture content fluctuates. On the average, however, the weathered copper plate takes on a color similar to that of the moist soil in this area.

A fifth source of possible error may be the differing effects of evaporation and condensation of moisture from the plate and the soil surface. The larger sensor used with the modified soil thermograph is not as sensitive to change in temperature as the thermistors and damps out most short-period fluctuation.

NET RADIOMETER

The temperature response of the bottom plate of the net radiometer is influenced by at least four sources of instrumental error. First, imperfect insulation may permit conduction of heat from the warmer to the colder plate. Thus at night the temperature reading of the bottom plate of the net radiometer may be too low because of conduction of heat upward through the insulation to the colder upper plate. This situation would be reversed during the daytime when the upper plate becomes the warmer. A conduction correction based on the temperature difference between the two plates can be determined, and this error source corrected for. Instrumentation for determination of the conduction constants was not available, so the uncorrected temperature readings were used.

Second, short-wave radiation reflected from the soil or snow surface during daylight hours causes the lower plate to have a higher temperature than the soil or snow surface which is radiating at a longer wavelength. This factor is not constant with the sun's altitude, but varies with the albedo of the surface, the amount and type of clouds, etc., and so can be considered only qualitatively.

Third, moisture tends to condense between the polyethylene or Saran Wrap layers covering the plates of the net radiometer. Since very thin layers of moisture in the form of liquid water absorb strongly in the infrared [8], nighttime observations are invalid if moisture is condensed between the layers of plastic or on the upper surfaces of the net radiometer covers. Because frequent changes of the covers were necessary, the radiometer could not be left unattended for long periods while its temperatures were being recorded. According to Kuhn [9] the moisture problem has been eliminated by flushing and sealing the unit with dry nitrogen.

A fourth source of possible error, for which no correction has as yet been determined, is the effect of wind upon the temperature indicated by the net radiometer. This effect is not particularly important when computing net radiation since the effect should be the same on

both plates. When using the lower plate only, however, it is reasonable to assume that some correction should be applied. A simple test made by shielding one net radiometer from the wind and not shielding another showed that with wind speeds of 10 or 15 m.p.h. the correction may be of the order of several degrees. Kuhn [9] has eliminated the wind effects from the economical radiometer by ventilating with a cheap electric fan.

5. CONCLUSIONS

The soil plate technique gives quite satisfactory indications of the sensible air-ground interface temperature. The accuracy of the measurements depends, of course, on the reliability and sensitivity of the sensor, as well as upon the size. The soil thermograph gives adequate reliability, but is more sluggish than the other sensors tested.

The Suomi-Kuhn Economical Net Radiometer is satisfactory for test purposes and specialized studies, such as measurement of the effective temperature of snow cover at night, etc. It is subject to difficulties because of moisture condensation and the effect of strong winds.

The most satisfactory method tested of measuring the sensible air-ground interface temperature was the use of either a small thermohm or thermistor as a sensor, which gave continuous records of sufficient accuracy for temperature forecast studies. As has been indicated, no tests were made with thermocouples due to lack of proper recording equipment, but the use of the copper plate with a thermocouple sensor should give very satisfactory results. With a thermocouple it might be possible to reduce the size of the plate and at the same time maintain a better contact between the ground and the sensing element over a longer period of time than could be accomplished with a thermocouple alone.

ACKNOWLEDGMENTS

Most of this work was done while Mr. John C. Eberhardt was Meteorologist in Charge at the Salt Lake City Airport. Mr. Eberhardt passed away during June 1960. His encouragement and guidance were invaluable to us. We are deeply appreciative to Mr. Philip Williams, Jr., Research Forecaster, and Mr. Merle Brown, W.B. State Climatologist for Utah, for reviewing and criticizing the manuscript, and to the Weather Bureau staff for many valuable suggestions. Thanks are also given to the staff of the Weather Bureau station at the National Reactor Test Site in Idaho for loan of recording equipment, and to Mr. Ray Dixon for his aid in designing and constructing equipment. Special thanks are given to Mrs. Dorothy Nelson for helping to transcribe data, to Mrs. Lucianne Miller who transcribed and processed data and aided in preparation of the manuscript, and to Mrs. Helen Maxfield for typing the final draft.

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Notice of Change in Month Designation of *Monthly Weather Review*

The next issue of the *Monthly Weather Review*, appearing in mid-December will be designated No. 9–12, September–December 1960. Thereafter each issue will be named for the month in which it appears; January 1961 (vol. 89, No. 1) will be available in mid-January, etc.

This change will not affect the status of subscriptions. Annual subscribers will receive a full twelve issues, this September–December issue being counted as one. For example, a subscription which began with January 1960 would end with the March 1961 issue.

A FORMULA FOR APPROXIMATION OF THE SATURATION VAPOR PRESSURE OVER WATER

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[Manuscript received June 11, 1960; revised August 17, 1960]

The use of electronic digital computers in scientific fields has made common the application of mathematical formulations of a much higher order of complexity and sophistication than was thought possible a generation ago. Yet, paradoxically, computer economics have made it urgent to seek mathematical simplifications, especially for commonly computed functions, to minimize computer time and the need for storage capacity. The kind of simplification to be sought in a formula is the use of only the elementary arithmetic operations in as few computer steps as possible.

Many approximation formulae have been developed for functions common to general mathematics. A widely used and well-worn collection of such approximations is that of Hastings [1]. Some areas of specific interest to meteorology, however, are as yet relatively untouched.

The hygrometric functions are basic and are used extensively in meteorology. Therefore, approximation formulae for these functions can be a valuable tool for meteorological computer applications. The author [2] presented such an equation for approximating relative humidity from dry bulb and dew point temperatures.

The equation presented here approximates the saturation vapor pressure over water with reasonable accuracy for temperatures in the range $-60°\text{F.} < t < 130°\text{F.}$:

$$e_s \cong (0.0041t+0.676)^8-0.000019|t+16|+0.001316 \qquad (1)$$

where e_s is the saturation vapor pressure over water in inches of mercury, and t is the temperature in °F.

The equivalent equation in metric units is:

TABLE 1.—*Comparison of values of e_s (in. Hg) computed from the Goff-Gratch formula and from approximation formula (1).*

t (°F.)	Goff-Gratch	Approximation	Error
−60	0.001651	0.001649	−0.000002
−40	0.005584	0.005582	−0.000002
−20	0.01668	0.01674	+0.00006
0	0.04477	0.04462	−0.00015
20	0.10960	0.10962	+0.00002
40	0.24767	0.24813	+0.00046
60	0.52160	0.52209	+0.00049
80	1.0323	1.0319	−0.0004
100	1.9334	1.9339	+0.0005
120	3.4477	3.4625	+0.0148

$$e_s \cong 33.8639\ [\ (0.00738\ t+0.8072)^8 -0.000019|1.8t+48|+0.001316] \qquad (2)$$

where e_s is in mb., and t is in °C.

If values of e_s computed by the accurate (but complicated) Goff-Gratch formula [3] are taken as a standard, the error of approximation using formula (1) is indicated in table 1. The relative error of approximation, in terms of percentage divergence from Goff-Gratch computed values, is shown in figure 1.

It may be of interest to note that the generally accepted equations, such as the Goff-Gratch formula for saturation vapor pressure over water, are themselves approximation equations in that they are the "best fit" to the known body of experimental measurements. If physical theory is ignored, and one seeks only to construct an empirical equation to fit the data reasonably well for a useful range, a simpler mathematical formula is frequently possible.

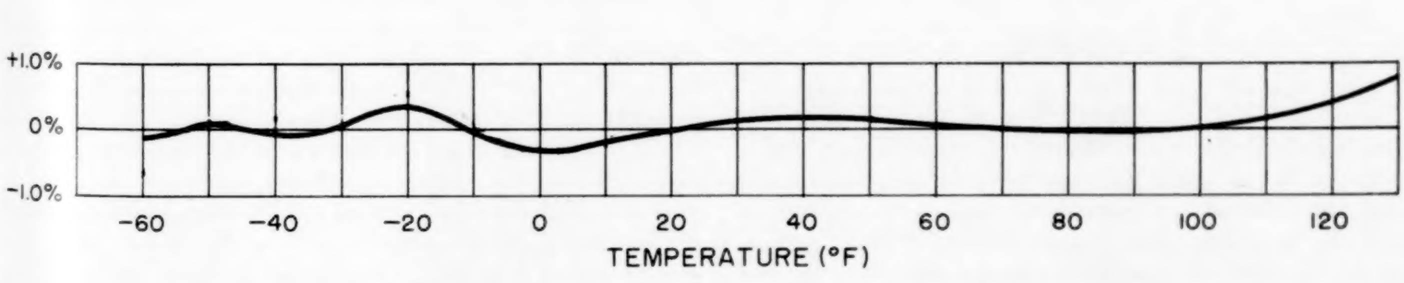

FIGURE 1—Percent error in the approximation $e_s \cong (0.0041\ t+0.676)^8-0.000019\ |t+16|+0.001316$.

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An Extension of a Table of Absorption for Elsasser Bands

The table referred to above was published by D. Q. Wark and M. Wolk in the July 1960 issue of the *Monthly Weather Review*. Regrettably, a number of entries in the table are illegible because of faulty printing. Therefore, Dr. Wark is offering a properly printed copy of the table to any reader who needs to make use of the information therein. His address is:

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USE OF TETROONS FOR MESOMETEOROLOGICAL INVESTIGATIONS

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August 1 and September 14, 1960

In a recent article House [1] discussed the optimum spacing of upper-air observations for the detection of mesoscale meteorological systems such as instability lines. In the conclusion to this article it is stated that the probability of detection of an instability line with the existing time and space distribution of upper-air stations does not exceed 10 percent. It is further stated that doubling the number of upper-air stations would increase the probability of detection by about 20 percent. Doubling or redoubling the existing number of upper-air stations is an expensive way to obtain the requisite data and as the author states, ". . . a network as dense as that suggested here by the computation of optimum spacing for incipient instability lines may never become economically feasible. . . . "

In view of the above, the question arises as to whether the problem should be considered only from the Eulerian or fixed-station standpoint. Recently, the Special Projects Section of the Office of Meteorological Research has been carrying out experiments on radar tracking of small, metalized, constant-level (superpressured) balloons. These balloons or tetroons (tetrahedron-shaped balloons) are 42 inches on a side, and with a weight of only 200 grams represent no danger to aircraft. With the addition of a radar reflective mesh, tetroon flights at levels under 5,000 feet have been tracked 100 miles. In the course of this tracking the horizontal wind field is obtained in detail and the vertical wind field can be closely approximated since the superpressured tetroons are rather easily forced off their equilibrium density surface by vertical air motions. With an accurate radar, such as the FPS-16, 3-dimensional wind velocity data accurate to 0.1 knot can be obtained at 30-second intervals. The obtaining of vertical motion in such detail is certainly unique. Furthermore, if a triad of tetroons could be released to float very nearly at the same level, the resulting distortion of the triad would indicate directly the vertical component of vorticity, the horizontal divergence, and the shearing and stretching deformation in the horizontal.

Drawbacks to the use of tetroons for mesometeorological investigations include the problem of when and where to launch, the problem of the tetroon being forced off its equilibrium floating level upon entering a region of precipitation, and the problem of tracking the tetroon when there are numerous precipitation echoes on the radar scope. An extremely light-weight transponder has been developed for attachment to the tetroons and this may mitigate the latter problem. A more general problem involves the fact that knowledge of the horizontal and vertical temperature field is also of great importance in mesometeorological studies and this cannot be obtained readily from tetroon flights at the present time.

In summary, the horizontal sounding system seems a logical complement to the vertical sounding system. Just as it is natural that the wind and temperature structure in the vertical be delineated by vertical soundings, so it is natural that the wind and temperature in the horizontal be delineated by horizontal soundings. In the past we have not had the capability for carrying out extended, constant-level balloon flights without the use of a ballasted system, but the superpressured-balloon technique appears to provide a highly suitable solution to this problem. Furthermore, the steady expansion of radar networks and the overlapping coverage of large areas represents an "in being" tracking system. While not all of the strictly weather radars are really suitable for tracking purposes, their capabilities could be explored. In particular, the usefulness of the WSR-57 radar for tetroon tracking should be determined. Given a radar tracking network, the cost of the tetroon system is modest, only about $20 apiece for balloon and radar-reflective mesh. This is considerably less than the cost of rawinsonde expendables. Therefore, it would appear desirable to make a few trial tetroon flights in the vicinity of severe storms, both for the purpose of delineating the problems involved and for the purpose of illustrating the usefulness of the resulting Lagrangian-type data.

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1. D. C. House, "Remarks on the Optimum Spacing of Upper-Air Observations," *Monthly Weather Review*, vol. 88, No. 3, Mar. 1960, pp. 97-100.

REPLY

D. C. HOUSE

Severe Local Storms Center, U.S. Weather Bureau, Kansas City, Mo
August 10, 1960

Dr. Angell brings up for discussion the question as to whether the problem of securing upper-air observations should be considered only from the Eulerian or fixed-station standpoint, particularly with regard to the problem of detection of mesoscale meteorological systems.

There are several reasons why such a discussion is timely. Foremost among these is the fact that the press of modern living demands that the weather forecast be more precise in regard to time or occurrence, amount, and location of any hazardous meteorological event. Alternatively, it has been suggested that the meteorologist produce a forecast in terms of the probability of the meteorological event occurring. Simultaneously, more of the National Meteorological Services' budget is being expended for fewer upper-air observations. This has come about in recent years through the utilization of more expensive and more accurate fixed-station observational equipment. Concurrent with this development there has been a significant reduction in the number of supplementary wind observations from the pibal network. Even though the meteorologist may have the knowledge and skill required to render a precise prediction and/or a statement of the probability of the event occurring, his ability to produce consistent results is in the final analysis related directly to the extent to which the observational network approaches an optimum design with respect to the scale (time and space) of the meteorological event he must predict.

The question is frequently asked as to the number and frequency of upper-air observations needed to predict severe local storms. The same question must also be asked with respect to other hazardous phenomena such as hurricanes, heavy rains, and heavy snows. The question of course cannot be answered meaningfully unless it is qualified by the acceptable time and space tolerances for the prediction. Once the tolerances have been decided upon, a network of surface and upper-air observations can be designed and its cost weighed against the economic benefit to be derived.

The development of an optimum network need not be entirely of the fixed-station type. As Dr. Angell suggests, there are strong arguments for the type of horizontal sounding system complementing the existing vertical sounding system. This argument stems from the basic equations of motion and the derived equations such as the vorticity equation and the divergence equation whose practical solutions are at present only approximations because of our inability to measure with precision such variables as the deviation between actual and geostrophic wind. An experimental network of stations capable of releasing and tracking the tetroons preceding a severe local storm outbreak or preceding the occurrence of heavy precipitation would indeed be invaluable in delineating the problems involved and subsequently for determining the optimum network needed for prediction.

HIGH LEVEL THUNDERSTORMS OF JULY 31–AUGUST 1, 1959

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[Manuscript received June 29, 1960; revised August 31, 1960]

ABSTRACT

The high level thunderstorms which occurred in Montana and northern Idaho on July 31 and August 1, 1959 resulted in critical lightning-caused fire conditions. These storms are described and the source of moisture and the instability which initiated them are discussed. It is pointed out that the reasons for the large number of lightning fires were the hot and critically dry conditions existing at the onset of these storms and the lack of any appreciable amount of precipitation with these storms rather than an excessive number of lightning strikes. The variation of the number of lightning strikes with different types of thunderstorms and the relation between the number of lightning strikes and the number of lightning-caused fires are discussed.

1. INTRODUCTION

Thunderstorms are usually classified as air-mass, frontal, or orographical. In some areas, especially in the mountainous areas of the West, there is the additional high-level type thunderstorm. In most cases, the separation of the storms into these categories is not clear-cut and any particular thunderstorm may be a combination of more than one type.

The high-level type thunderstorms are equally vague and difficult to fit into any simple pattern. These storms may be initiated by lifting of the upper layers by the passage of an upper cold front or a low pressure trough moving across the area. The storms may be started by the increased instability caused by the advection of cold air aloft. In some situations the air is sufficiently moist in all layers, while in other storms the air is moist and unstable only in the upper layers. In some cases, there is a rapid progression of the storms across the area. The high-level thunderstorms usually are associated with little or no precipitation reaching the ground and present a serious problem for fire control operations.

2. DESCRIPTION AND HISTORY OF THE STORMS

The thunderstorm period of July 31–August 1, 1959 over the Montana and northern Idaho region offers a striking example of high-level thunderstorms which can cause serious fire control problems. Figure 1 shows the area involved with the number of lightning-caused fires in each National Forest. In all, some 240 lightning-caused fires were reported at the end of the first day; during the next few days were reported an additional 100 fires which had been started by lightning strikes occurring on either July 31 or August 1.

The first signs of the storms were seen early on the morning of July 31. The radiosonde report for 1200 GMT (0500 MST) at Boise, Idaho indicated a decided increase in moisture above the 18,000-foot level. Early morning weather reports revealed widespread altocumulus and altocumulus castellatus cloud formations with considerable virga streaming from these clouds. Aircraft observations at Missoula, Mont. indicated the base of these clouds was between 17,000 and 18,000 feet m.s.l. with an indicated cloud base temperature of −8° C.

Thunderstorms started developing over the eastern sections of the Nezperce National Forest by 1445 MST. By 1800 MST, thunderstorms had either formed or spread over all of the Nezperce and Bitterroot National Forests, and the eastern sections of the Lolo National Forest.

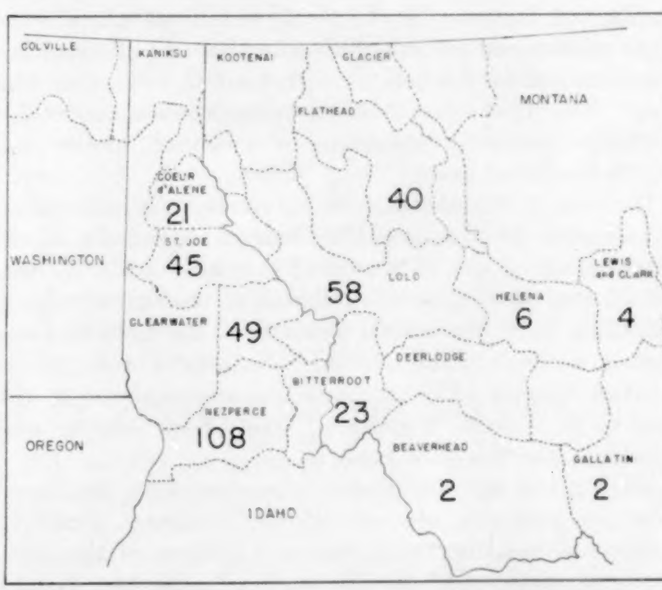

Figure 1.—Number of lightning-caused fires started by the July 31 and August 1, 1959 thunderstorms on each National Forest.

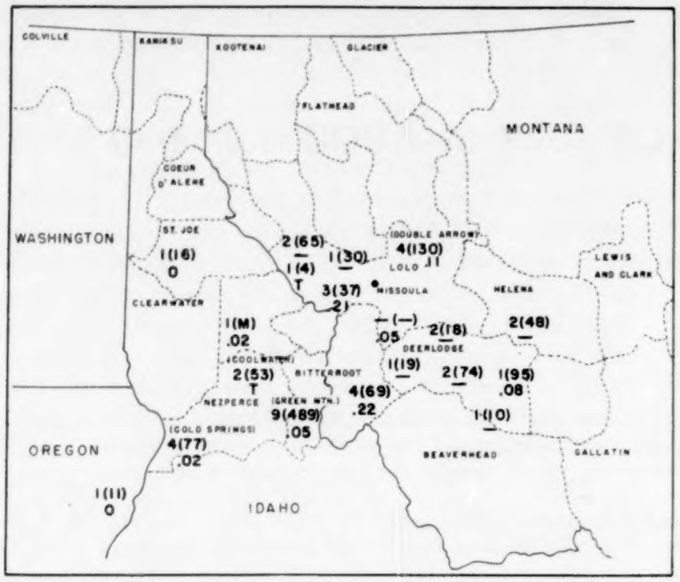

FIGURE 2.—Number of thunderstorms, total number of lightning strikes (in parentheses), and the total precipitation reported during the storm period.

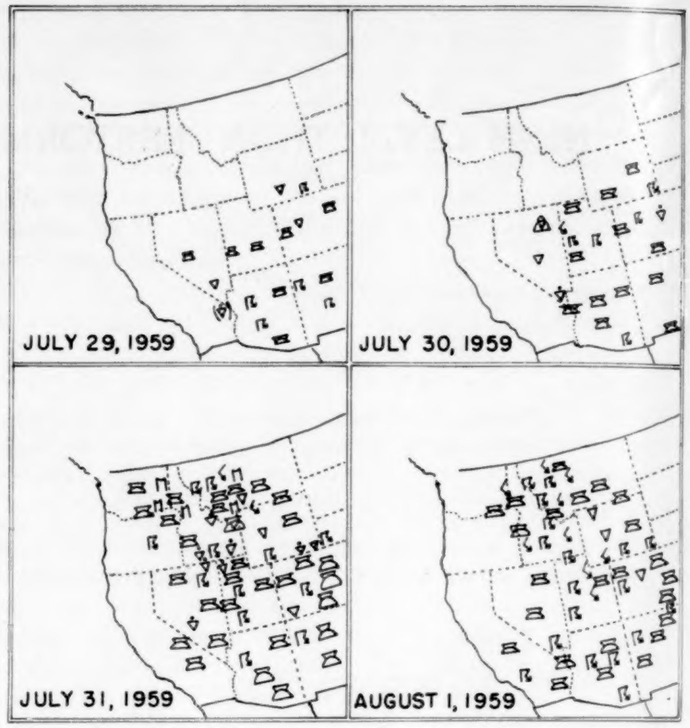

FIGURE 3.—Progression of the convective cloud activity and thunderstorms from July 29 to August 1, 1959.

Another set of thunderstorms apparently developed farther to the north over the Clearwater and St. Joe National Forests with the first storm reported at 2130 MST. These thunderstorms continued to form or spread over the northern sections of the Lolo and the southern sections of the Flathead National Forests and continued until shortly after midnight. The greatest number of lightning strikes was reported with the southern, or the earlier, set of storms.

During the early morning of August 1, a set of thunderstorms developed over the central section of the Lolo National Forest around 0400 MST with a relatively small number of lightning strikes. By daybreak there were again widespread reports of altocumulus and altocumulus castellatus cloud formations with trailing virga over the area. The 1200 GMT (0500 MST) radiosonde report for Spokane indicated considerable moisture above the 18,000-foot m.s.l. level.

Between 0700 and 0900 MST, thunderstorms had broken out all over the Nezperce, the Clearwater, and the southern sections of the Bitterroot National Forests. These storms continued to form or spread to the east-northeast extending over the central sections of the Lolo and the western sections of the Deerlodge National Forests. The greatest number of lightning strikes was reported at the Coolwater, Green Mountain, West Fork Butte, and Double Arrow Lookout Stations.

During the early afternoon, thunderstorms developed over the southern sections of the Nezperce, southern sections of the Bitterroot, southern sections of the Lolo, northern sections of the Beaverhead, and the Helena National Forests. The greatest number of lightning strikes was reported at the Cold Springs and Green Moun-

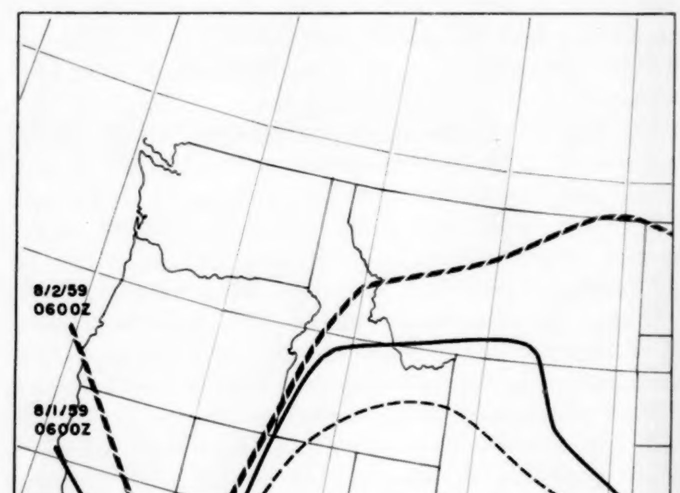

FIGURE 4.—Progression of the 50° F. surface dew points northward during the storm period.

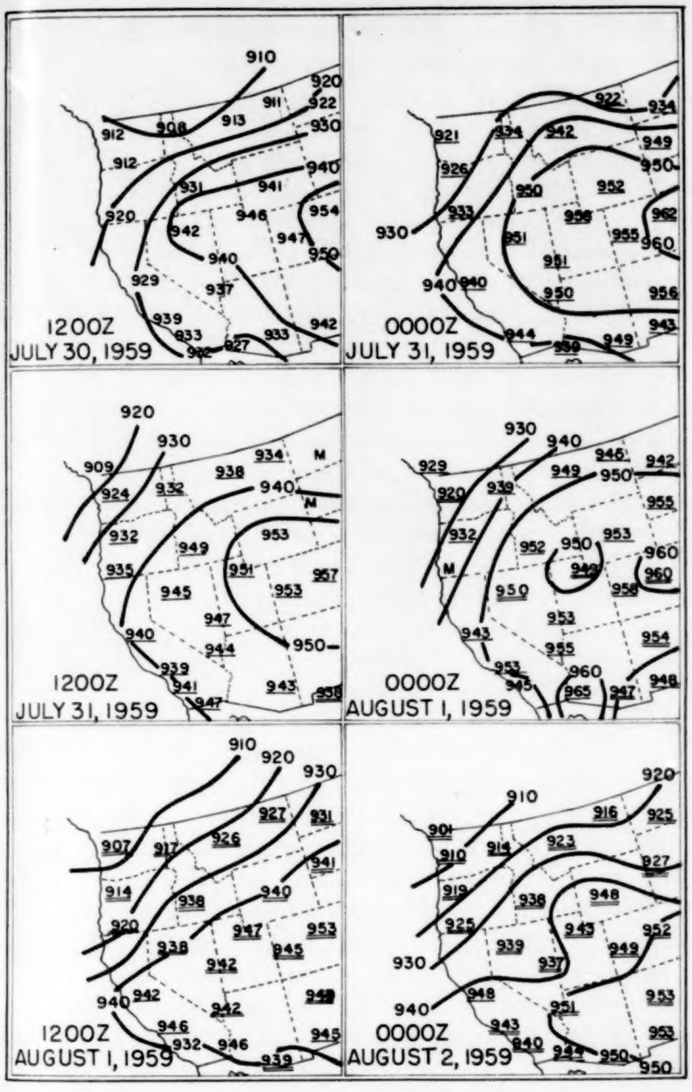

Figure 5.—Sequence of 500-mb. charts during the storm period. Single underscore indicates 24-hr. increase in height; double underscore a 24-hr. decrease in height.

tain Lookout Stations and over the Deerlodge National Forest. Another set of late afternoon and early evening thunderstorms developed over the southern sections of the Nezperce and the southern sections of the Bitterroot National Forests with a large number of strikes near Cold Springs and Green Mountain.

The storms appeared to develop over fairly wide areas at irregular times during each set of storms. While there was some evidence of spreading with the general wind circulation toward the ENE or NE, there was no rapid or well defined spread as was observed in the July 21-22 and the August 24–25, 1955 storms reported in an earlier article [1].

Figure 2 shows the number of individual thunderstorms, the total number of lightning strikes, and the total precipitation reported at each station during the entire storm period.

The thunderstorms on July 31 appeared to develop out

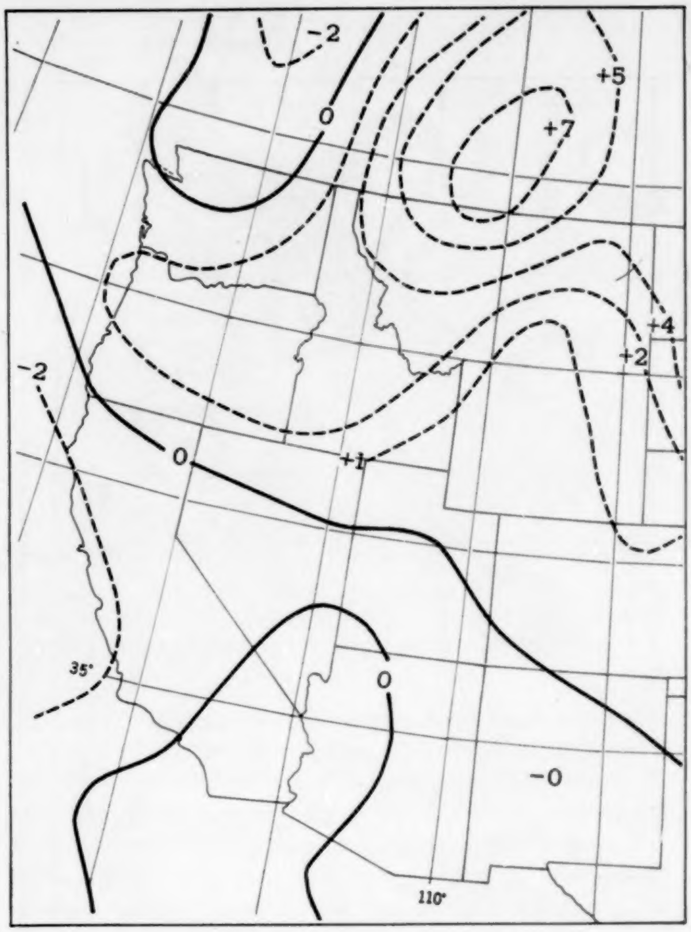

Figure 6.—Initial vertical motion (cm. sec.$^{-1}$) for 0000 GMT August 1, 1959.

of the altocumulus deck of clouds with the bases remaining between 17,000 and 18,000 feet m.s.l. except locally slightly lower in some heavier precipitation. The total vertical growth of the storm clouds was not very great at any time. The tops, as seen in Missoula, did not appear to be over 25,000 feet m.s.l. There were only occasional brief and locally heavy showers with some hail but the total amounts, as seen in figure 2, were quite low and scattered. Some locally gusty surface winds of 40 to 50 knots were reported at some stations.

The bases of the clouds and the storms during the day on August 1 were slightly lower than on the previous day, but were still around 15,000 feet m.s.l. In general there was more precipitation with the storms on August 1 than with the storms on July 31.

3. SOURCE OF MOISTURE AND INSTABILITY

A study of the source of moisture for these storms shows that the moisture apparently worked northward from the Arizona-Nevada area, and in turn had its origin as an aftermath of hurricane Debra. The progression of the storm and convective activity is shown in figure 3. The progression of the 50° F. surface dew points northward is shown in figure 4.

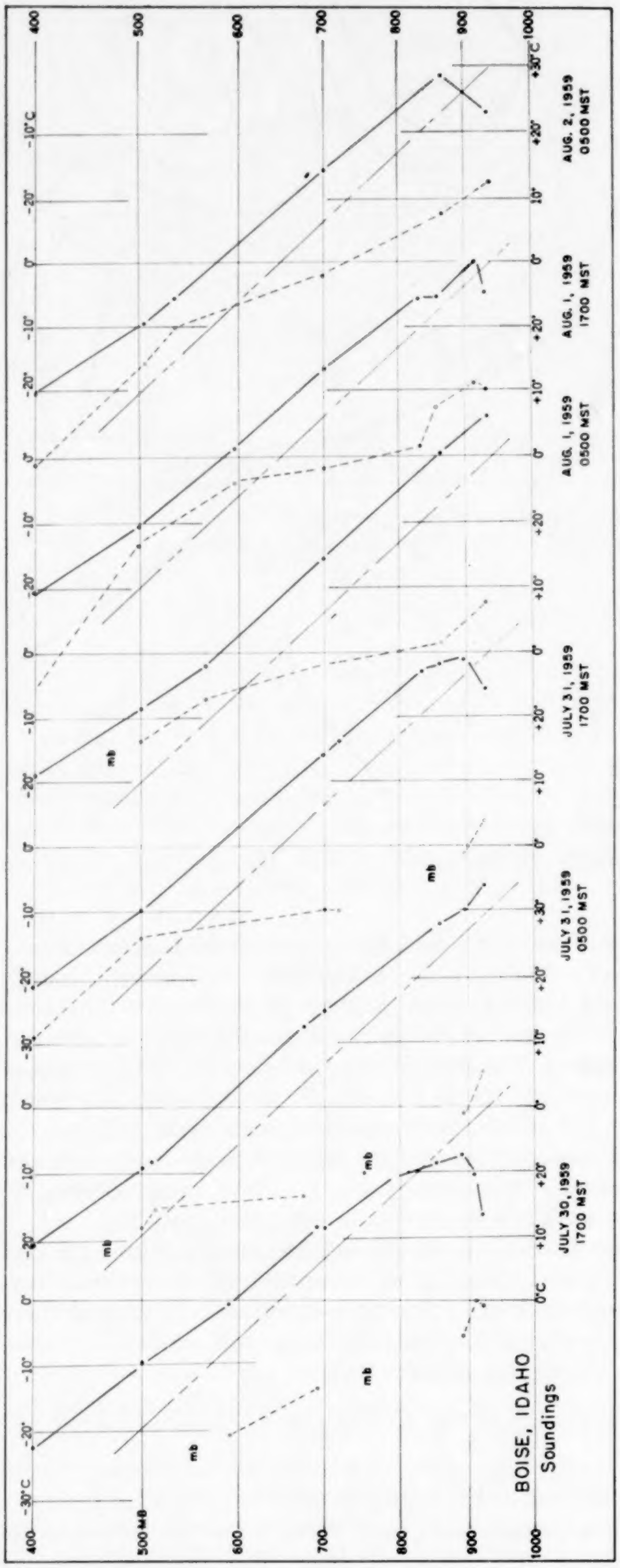

FIGURE 7.—Sequence of radiosonde reports for Boise, Idaho during the storm period.

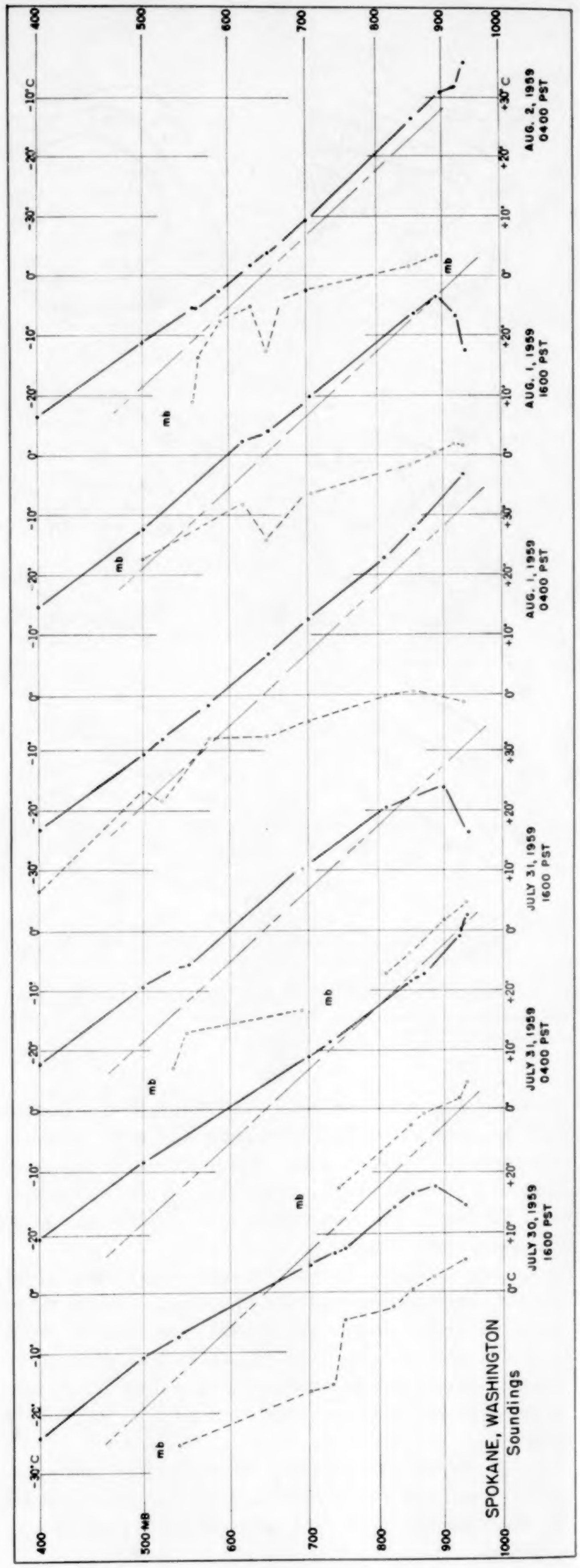

FIGURE 8.—Sequence of radiosonde reports for Spokane, Wash. during the storm period.

Many other high level thunderstorms have been associated with the deepening of an intense cold low pressure area off the northwestern coast or the passage of an upper cold front or low pressure trough which could be easily traced on the 500-mb. charts. In this case the 500-mb. charts (fig. 5) show no such progression. The 24-hour pressure-height changes showed general increases over the West up to the afternoon of July 31 (0000 GMT August 1) except for the decreases which set in at Winnemucca, Nev. and Salt Lake City, Utah. Between this time and late afternoon August 1 (0000 GMT August 2) there were decided decreases over the entire area. Similar results occurred at the 700-mb. level but are not shown.

A study of the initial vertical motion chart (fig. 6) for 0000 GMT August 1 shows widespread upward vertical motion over the Montana-Idaho area on the afternoon of July 31. On the previous day, there had been either no marked upward vertical motion or slight downward currents over this area southward.

The change in the vertical motion and stability patterns can be seen in the radiosonde reports for Boise and Spokane (figs. 7 and 8). There is some evidence of subsidence in the upper levels through the early morning of July 31 which is in agreement with the increasing pressure-heights on the 500-mb. charts for this period.

Increasing moisture and instability is apparent in the upper levels in the afternoon sounding of July 31 at Boise and the early morning sounding of August 1 at Spokane. This agrees with the upward vertical motions and decreases in the 500-mb. pressure-heights. The late afternoon sounding for August 1 at Spokane shows the return of subsidence and drier air in the upper levels.

In spite of the slight increase in the surface moisture, as was shown in the northward spread of the 50° F. dew point, there was a lack of sufficient moisture and instability in the lower levels to initiate the thunderstorms. It is apparent that these thunderstorms can only be explained on the basis of the increase in moisture and instability in the upper levels. On the basis of the early morning radiosonde and the cloud data on July 31, thunderstorms were forecast for late afternoon and evening. On the morning of August 1, thunderstorms were forecast to continue throughout the day and evening with decreased activity on August 2.

4. RELATION OF LIGHTNING STRIKES AND LIGHTNING-CAUSED FIRES

The question arises as to why this thunderstorm period produced so many lightning fires. There are several interesting aspects to this question. While these cannot all be considered in this paper, perhaps some insight can be gained on the subject.

The weather conditions had been such that the surface fuels were very dry at the onset of these thunderstorms. The entire month of July had been very dry and the temperatures were quite hot near the end of the month. The total precipitation was only 0.13 in Missoula up to July 31.

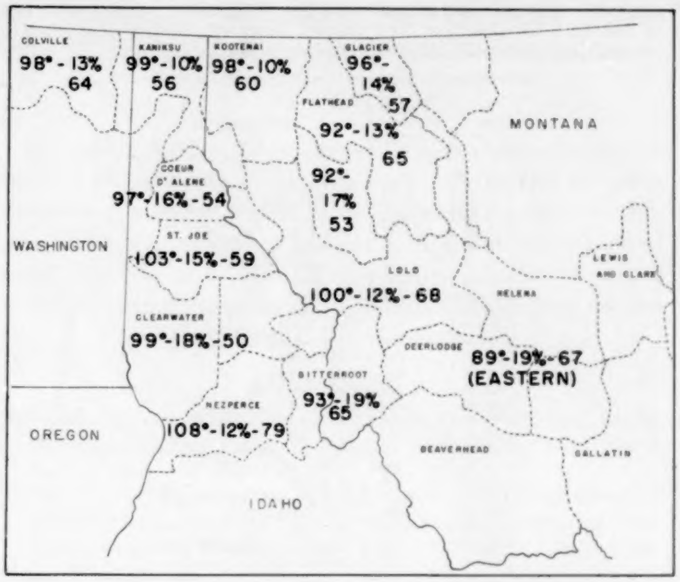

FIGURE 9.—Maximum surface temperatures (°F.), minimum relative humidities (percent) and the highest burning indices on each National Forest on the afternoon of July 31, 1959.

The only lightning at Missoula had been reported on July 3. This low precipitation and thunderstorm activity was quite general over the entire region. For the 23 days from July 8 to July 30, there had been only 18 National Forest-thunderstorm days on the 10 western forests and 26 on the 5 eastern forests. Project Skyfire lookout stations reported only 25 percent of the normal number of thunderstorms and 16 percent of the normal number of lightning strikes.

The main reason for this lack of precipitation and thunderstorms was the existence of a persistent and strong high pressure ridge circulation at the upper levels (700, 500, and 250 mb.) [2]. The influence of the deep cold low pressure area which is usually present off the northwestern coast was significantly weak during July. Only a few minor troughs moved eastward and they were confined north of the Canadian border and did not affect the Montana area. What little storm activity did occur was mostly isolated and scattered.

The conditions at the onset of the storm period were hot and dry. As can be seen in figure 9, the maximum surface temperatures were in the upper 90's or lower 100's and the minimum relative humidities ranged from 10 to 20 percent. The fire-danger rating, or burning index, based on current fuel moisture reading, the 5-day total fuel moisture reading, the wind speed, and the relative humidity, had been building up during the last part of July. At the onset of this storm period, the maximum burning index ranged from 50 to 70.

In the comparison of this thunderstorm period with other high-level storms, the radiosonde data are highly significant. The storms of July 1–8, 1955 and July 7–8, 1959 were initiated by the advection of cold air aloft or the passage of a low pressure trough aloft. But the

1960

FIGURE 8.—Sequence of radiosonde reports for Spokane, Wash. during the storm period.

TABLE 1.—*Comparison of total number of lightning strikes with type of storm. (Strikes per day for 25 days of greatest frequency of strikes in 5-year period, in descending order.)*

Date	Total number of strikes	Type of storm
7-18-56	1262	Air mass
7-16-55	1088	Frontal zone
7-13-56	1057	Cold front
7-13-57	1045	Cold front
7-20-56	853	Air mass
7- 9-56	755	Air mass
7-28-58	749	Air mass
7-17-58	739	Air mass
7-11-56	720	Air mass
7-31-56	714	Cold front
8- 1-59	694	Upper-level
7-17-55	668	Cold front
7- 9-55	657	Frontal zone
7-25-55	558	Cold low aloft
7-28-58	509	Air mass
7-19-57	504	Air mass
7-23-55	492	Air mass
7-18-58	489	Air mass and weak low aloft
8- 9-56	448	Cold front
7-21-55	442	Air mass
7-21-57	412	Low pressure trough aloft
7-22-55	409	Cold low aloft
7-12-56	380	Air mass
8- 6-56	370	Low pressure trough aloft
7-15-55	364	Frontal zone

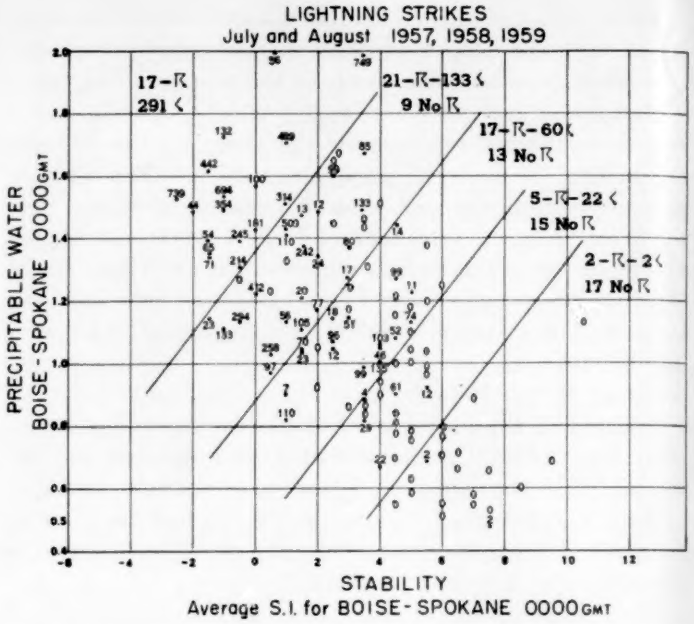

FIGURE 10.—Number of lightning strikes over the region plotted against the two variables: total precipitable water (gm.) from the 0000 GMT Boise and Spokane soundings and the average stability index (S.I.) from the 0000 GMT Boise and Spokane soundings. Data are separated into 5 classes with increasing chance of thunderstorm occurrence and average total number of lightning strikes.

radiosonde observations indicated that the air was quite moist at all levels and the resulting precipitation was generally heavy. The conditions for the July 31–August 1, 1959 storm period indicated that sufficient moisture and instability to initiate thunderstorms occurred in the upper levels only. This was similar to the storm period of August 24–25, 1955 which also produced little precipitation.

With the base of the clouds and storms quite high and the air very dry below the clouds, most of the precipitation appeared as virga and little reached the ground.

The question arises whether these high-level storms produce an excessive number of lightning strikes. Some data have been gathered on this problem during the past 5 years of Project Skyfire operations. Table 1 gives the tabulation of the total number of cloud-to-ground lightning strikes for the 25 days with the greatest number of strikes along with the classification of the thunderstorms on those days. While it is difficult to be completely certain of the above classification, it appears that more strikes occurred on the days with air-mass and frontal types of thunderstorms than with the high-level type thunderstorms. This would indicate that one would not expect to find more strikes on the days with high-level thunderstorms. There were only 262 lightning strikes reported on July 31 and 694 on August 1.

In the scatter diagram shown in figure 10, the number of lightning strikes is plotted against two variables: the averages of the 0000 GMT Boise and Spokane stability indices (Showalter) and the total precipitable water computed from the 0000 GMT Boise and Spokane radiosonde data. The number of lightning strikes, as well as the chance of thunderstorm occurrence, seems to be strongly dependent on these two variables. While there is considerable scatter, it is possible to separate the lightning strike data into classes with both the average total number of lightning strikes and the chance of thunderstorm occurrence increasing toward the corner of the chart with the greater instability and higher precipitable water content.

The high-level type thunderstorm with the moisture and instability restricted to the upper levels can not be expected to appear near the corner of the scatter diagram with high overall precipitable water and instability index. Therefore, these high-level storms would not be expected to show as great a number of lightning strikes. It has also been speculated that more strikes should be associated with the storms with the greatest vertical development. The high-level storms with relatively small vertical development should not be expected to have so many lightning strikes.

It can be concluded that the large number of lightning fires set off during this storm period was due to the extremely hot and critically dry conditions at the surface at the onset of these storms and to the lack of any appreciable amount of precipitation during these storms, rather than to any excessive number of actual cloud-to-ground lightning strikes.

In addition to the type of surface fuel, the dryness of the fuels, and the amount of precipitation associated with the lightning strikes, another important factor in the efficiency of lightning strikes in producing fires is the amount of current carried by the strikes and the duration of the strikes. Norinder [3] refers to the strikes with unusually heavy current and of long duration as

"gangster" type strikes. These strikes should have a greater fire-starting potential. Much more research is needed along these lines.

5. CONCLUSIONS

As a result of this study, it is suggested that the term high-level type thunderstorm be restricted to the situations where sufficient moisture and instability for thunderstorm initiation are to be found in the upper levels only. The actual triggering action may be the advection of cold air aloft, the passage of an upper cold front or low pressure trough, or as in this case, widespread upward vertical motion. The actual speed of motion of these storms may vary considerably, ranging from nearly stagnant conditions to rapidly progressing systems. These storms are all associated with high cloud bases and with little or no precipitation reaching the ground.

Other storm situations with moist conditions at all levels, even though they may be initiated by the advection of cold air aloft or the passage of an upper low pressure system, have much lower cloud bases and are associated with considerable precipitation; they should be classed along with the other air-mass or frontal types of storm.

ACKNOWLEDGMENTS

The writer wishes to express his appreciation to the members of the Project Skyfire staff for the use of some of their data and for their cooperation and interest in this work. The writer wishes to thank Mrs. Ivalou O'Dell of Project Skyfire and Miss Sarah Kroll of the Weather Bureau for their valuable help in the compilation of the data and in the preparation of the paper.

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THE WEATHER AND CIRCULATION OF AUGUST 1960

A Month Dominated by a Circulation Reversal

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1. CONTRASTING CIRCULATION PATTERNS WITHIN THE MONTH

A major reversal in the large-scale 700-mb. mean circulation over North America and adjacent oceans occurred from the first half to the last half of August 1960. This intra-monthly change contributed substantially to the weather and circulation of the whole month. It is particularly notable because summer months are generally subject to considerable persistence. Consequences of the intra-monthly circulation change included a readjustment of the weather anomalies both within the month and from the preceding month.

AUGUST 1-15

The 15-day mean circulation for the first half of August, shown in figure 1A, clearly indicates a pattern of four rather symmetrical cyclonic vortices in the Northern Hemisphere. Three were located around 60° N., but the fourth (over Asia) was 10° farther north. The wave number at middle and lower latitudes was greater by at least one, but not so well defined.

An interesting observation concerning the cyclonic vortices is derived from the anomalous height distribution at 700 mb. (dotted lines in fig. 1A). First, note the intensity of the Low centers. Beginning with the −170-ft. center over the Bering Sea, and continuing in a clockwise direction, the negative anomalous height centers become progressively deeper, with maximum intensity (−340 ft.) over Quebec.

Of further note are the wavelengths involved. There was a gradual but definite increase in the wave spacing, beginning with the trough in the north central Pacific, and moving in a clockwise direction. At 55° N. there was a wavelength of 115° of longitude from the trough in eastern North America to the next trough upstream in mid-Pacific. The blocking in polar latitudes centered over northern Greenland undoubtedly influenced the asymmetry of the pattern and in some manner probably contributed to the unusual wave spacing.

The western lobe of the subtropical ridge in the Pacific was quite strong (+210 ft.) and displaced some 5° of latitude northward from the August normal [1]. The eastern portion of the ridge was also higher than normal, and displaced northward a similar amount. The trough in the central Pacific was deeper than normal at higher latitudes and much weaker at middle latitudes. Another item of interest was the rather strong ridge in western Canada, which was directly north of a weaker-than-normal trough along the west coast of the United States.

AUGUST 16-31

A comparison of the 700-mb. circulation of the last half of August (fig. 1B) with the first half (fig. 1A) reveals most impressive changes, especially over North America. Strong deepening in western North America was apparently resonant with amplification in the Pacific. Contributory to or sustaining the anticyclogenesis in the western Pacific was intense low-latitude activity in the southwestern Pacific.

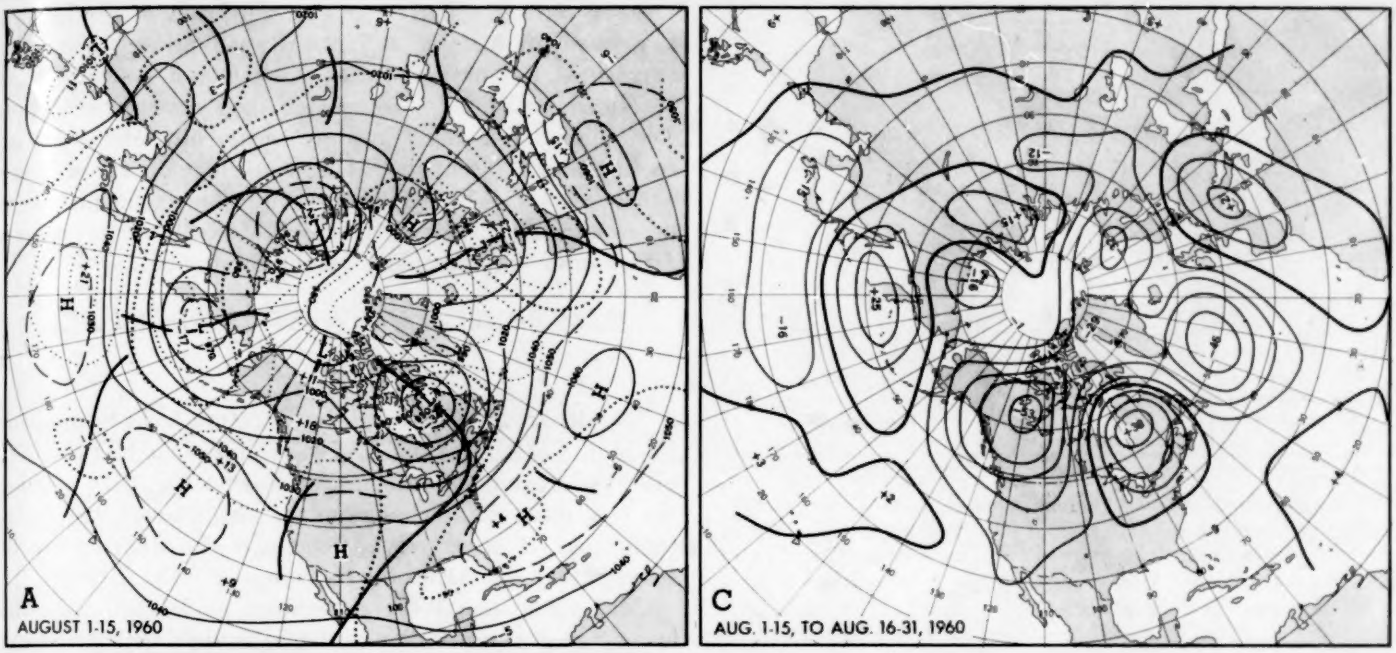
In retrospect, cyclogenesis in western North America was a logical development. Since the wavelength from eastern North America to the central Pacific was extremely long, and since the westerlies appeared too weak to support that wavelength, an untenable situation developed. Accommodation occurred in the form of a new, full-latitude trough in western North America. Downstream, the trough over eastern North America was replaced by a ridge; the ridge in mid-Atlantic moved east as a trough took its place during the last 15 days of August.

The result was a succession of intra-monthly height changes of alternating sign from eastern Asia eastward to Europe (fig. 1C). Maximum negative and positive changes in the Northern Hemisphere were contiguous over North America, with a −530-ft. height fall near Great Slave Lake and an opposing height rise of 380 ft. in Quebec. Note that as dispersion operated eastward from North America, progressive damping occurred in the magnitude of centers of height rise and fall.

The deepening trough in western North America is noteworthy not only as an anomaly of the planetary wave system, but also because of the accompanying temperature modification in the United States.

2. CONTRASTING TEMPERATURE PATTERNS IN AUGUST

Temperatures in the United States were subject to an oscillation from the first half of August to the last half, parallel to the circulation changes described above.



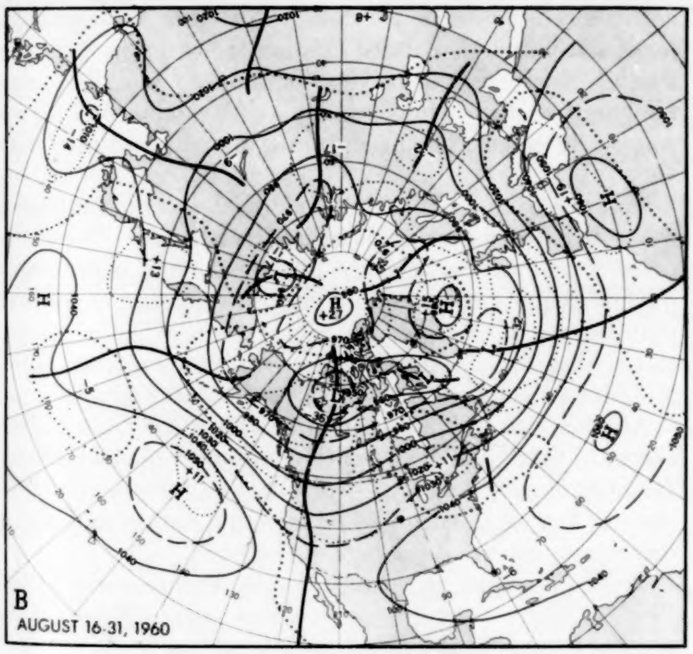


FIGURE 1.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for (A) Aug. 1–15, 1960, and (B) Aug. 16–31, 1960; (C) 700-mb. height change (tens of feet) from (A) to (B). The −530-ft. change near Great Slave Lake reflects the intense deepening in western North America.

AUGUST 1–15

Temperature departures from normal for the first 15 days of August are shown in figure 2A. It was very hot in the Southwest with much of northeastern Arizona at least 6° F. above normal. The heat in the Southwest was accompanied by a quasi-stationary anticyclone at 700 mb. (fig. 1A), abundant sunshine, and prolonged subsidence. Little cooling was realized from the northerly direction of the anomalous component of the upper level flow. This flow was effective, however, in the Pacific Northwest where a few stations from Montana to northern Oregon reported temperatures slightly below normal. Considering the weakness of the mean trough there, it is somewhat surprising that temperatures were not higher.

In the Northeast and throughout the Mississippi Valley, temperatures were as much as 4° F. cooler than normal. They were aligned approximately along the zone of below normal heights in and near the mean trough which extended from the Low over the Ungava Peninsula through New England to Texas. In the Middle Atlantic States warmer than normal temperatures coincided with a relatively strong westward extension of the Bermuda ridge.

AUGUST 16–30

Extreme cooling in the West from the Canadian Border to Mexico during the last half of August (fig. 2B) was directly related to the intense cyclogenesis at 700 mb. (fig. 1B). Stronger than normal northwesterly flow was responsible for several invasions of cool Pacific air masses west of the Continental Divide.

Temperature changes from the first half of August to the last half ranged as much as −6° to −8° F. (fig. 2C), as cooler than normal temperatures were widely reported from Arizona to Washington (fig. 2B). New daily minimum temperatures were recorded at several stations in the Northwest, following the injection of unseasonably cold air. An extreme example of the change of temperature regime was at Burns, Oreg., where a daily mean temperature of 78° F. was observed on August 12; on August 22, the daily mean was 46° F.

In response to the deepening trough in the West, a

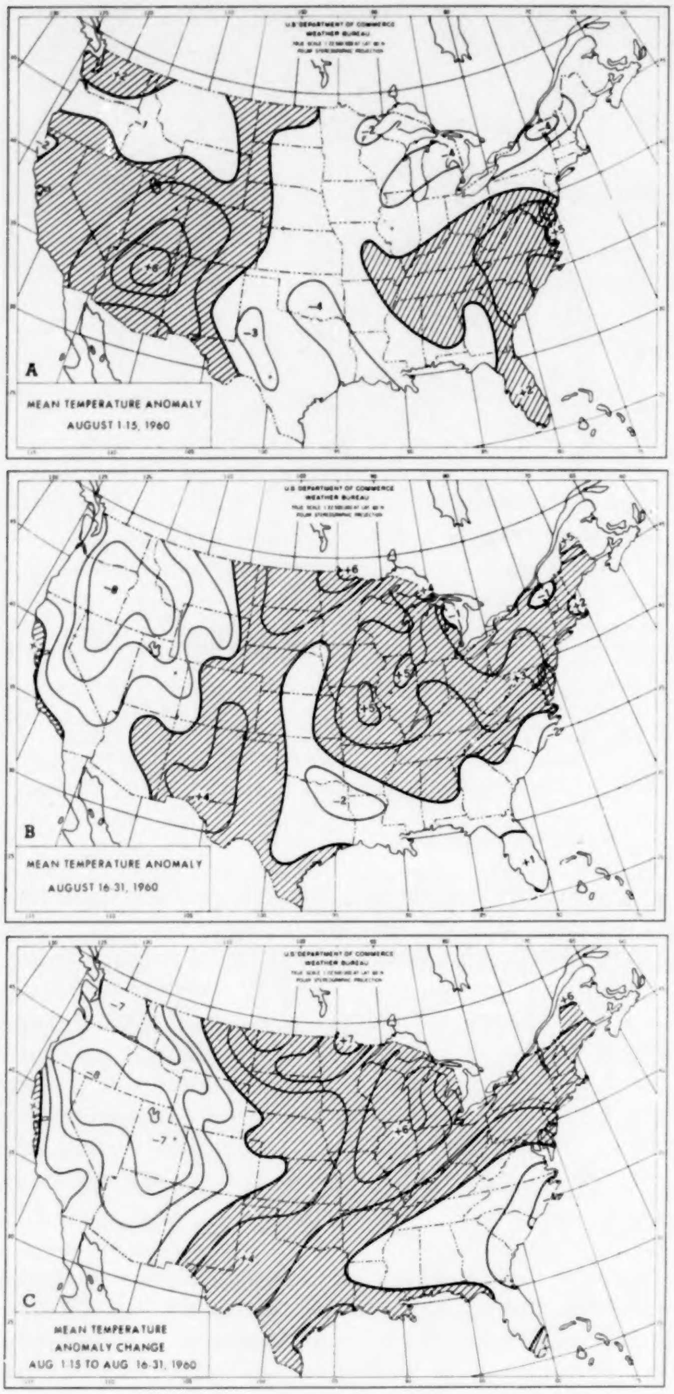


Figure 2.—Departure of average surface temperature from normal (°F.) for (A) Aug. 1–15, 1960 and (B) Aug. 16–31, 1960; (C) temperature change (°F.) from (A) to (B). Cooler air in the last half of August dominated the West from the Canadian border to Mexico.

general warming occurred immediately to the eastward. At International Falls, Minn., the daily mean temperature increased by 24° F. from August 14 to August 17. Warming in other areas was less spectacular, but rather general, east of the Rockies, except in the Southeastern States.

Some cooling occurred in the Southeast in the last 15 days of the month (fig. 2C), but it was neither of the same magnitude nor extent as the cooling and warming just described, principally because changes in the circulation were slight (fig. 1C). It may seem contradictory that cooling should occur under the mean ridge observed in the Southeast (fig. 1B). However, upper-level heights were below normal; there were also cooling effects of the onshore direction of the anomalous height component.

3. MONTHLY MEAN WEATHER ANOMALIES

TEMPERATURE

The departure of average temperature from normal for the month of August (fig. 3A) was similar in pattern to that observed during the last half of August (fig. 2B). Thus, the character of the change in the last 15 days was so intense that it effectively determined the distribution of temperature anomalies for the whole month.

Cold air in the West penetrated as far south as the lower San Joaquin Valley, but maximum departures from normal were centered in Idaho. New low temperatures for August and new daily minima were recorded in the Pacific Northwest at several stations. A daily mean temperature 19° below normal at Pocatello, Idaho, on August 16 is an extreme example of the cooling in that area.

Opposed to the cold in the Northwest was the continued warmth in the desert areas of the Southwest. Temperatures were not particularly abnormal, but persistently warm. August was the third successive month of warmer than normal conditions. A report from Winslow, Ariz., stated that daily maximum temperatures were 90° F. or more for 28 consecutive days, a new 30-year record.

Another belt of warm conditions from the Ohio Valley eastward to the Middle Atlantic States prevailed with little variation during August. Norfolk, Va., for example, was warmer than normal on 24 days of the month and had a mean temperature departure of +3.6° F.

From Nebraska to eastern Texas, thence eastward to Florida, cooler than average weather generally prevailed, but departures from normal were less than 2° F.

Since August was a particularly non-persistent month, it is appropriate to compare the temperature anomaly of August (fig. 3A) with that of July (fig. 3B). Warm air in the West in July was replaced in August with fairly cool air; a similar reversal took place on the Gulf Coast; cool weather in the East in July became warmer than normal in August; and from the Dakotas to the Southwest little change occurred.

The lack of persistence of temperature anomalies from July to August is best seen in figure 4. This figure represents the number of temperature class[1] changes from July to August at 100 stations. The unshaded

[1] Temperature anomalies are divided into the following classes: much above and much below (12½ percent occurrence each) and above, near normal, and below (25 percent occurrence each).

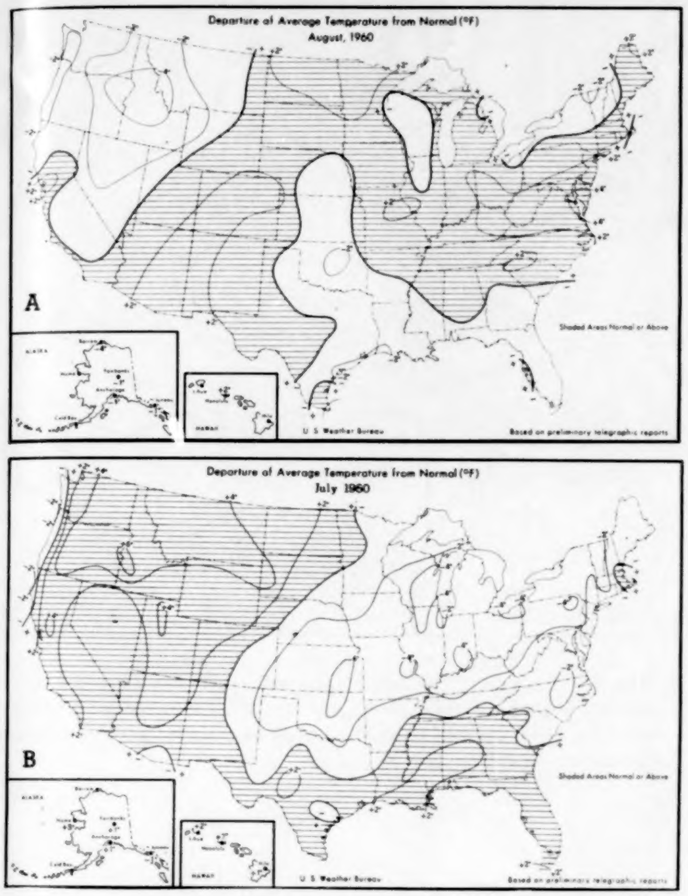


Figure 3.—Departure of average surface temperature from normal (°F.) for (A) August 1960, and (B) July 1960. Hatching shows area of warmer than normal anomalies; unshaded areas were cooler than normal. Note general reversal of pattern from July to August. (From [8].)

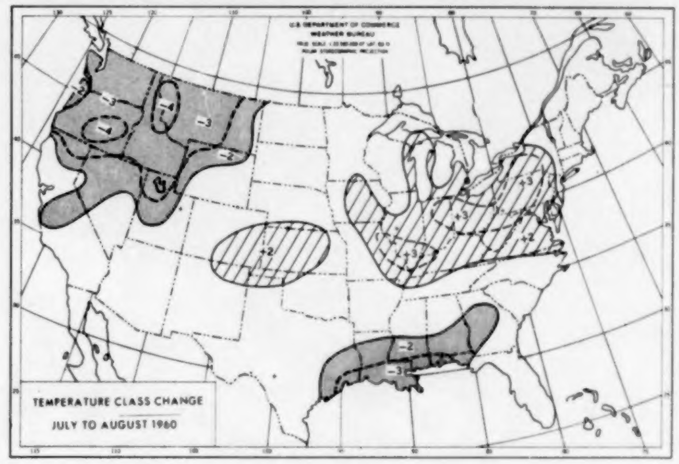


Figure 4.—Change in class of temperature anomalies from July 1960 to August 1960. In unshaded areas temperatures did not change by more than one class (out of five); hatched areas represent a warming of two or more classes; and stippled areas show cooling of two or more classes. Largest changes were in the Northwest where temperature anomalies changed from much above normal in July to much below normal in August.

portions of the map include those stations which reported a change of no more than one temperature class, thus delineating areas of relative persistence from July. A broad area in the Northwest (stippled) was two to four classes colder in August than in July. Also colder was the Gulf Coast, by two to three classes. The hatching portrays a warming of two to three classes. The area of warming was centered in the Ohio Valley and was roughly equivalent in size to the areas of cooling. Quantitatively, there was little difference between the two since 19 stations cooled two or more classes and 18 stations warmed by the same amount from July to August.

A tabulation of temperature class changes indicates a temperature persistence index of 63 percent, compared with a 16-year average of 82 percent for August [2]. It should be noted that persistence of 54 percent in August 1959 was particularly low, as was an index of 59 percent in August 1958. Thus, 1960 marked the third consecutive year in which July-August persistence of monthly mean temperatures has been subnormal.

Non-persistence of temperatures in August resulted principally from intra-monthly changes in the circulation. But the effects of the variability in the circulation were not confined to temperature; the distribution of precipitation was also influenced.

PRECIPITATION

Precipitation in several sections of the United States in August was much greater than normal (fig. 5). August rains alleviated drought in parts of Montana and Wyoming, but paradoxically southern Wyoming remained dry. Farther west, at Stampede Pass, Wash., a total of 5.06 in. of rain established a new August record, all but 0.08 in. of which fell in the last 18 days of the month. Most of the precipitation in the Northwest was associated with the deepening trough discussed above and illustrated in figure 1B.

No measurable rain was reported over much of California, and dry conditions extended as far east as western Kansas, where Goodland had only 0.29 in., the driest August of record.

Above normal precipitation in the Great Plains was coincident with a deep southerly mean flow of tropical Gulf air at sea level (Chart XI of [3]). In the Northern Plains both fronts and cyclone passages were frequent. Yet, actual amounts of rain were much greater in the Southern Plains, presumably a result of more widespread convection.

The maximum monthly precipitation (from early reports) fell at Vicksburg, Miss. The total was 16.58 in., of which 6.20 fell in one day. That station experienced the wettest August of all time and the wettest month

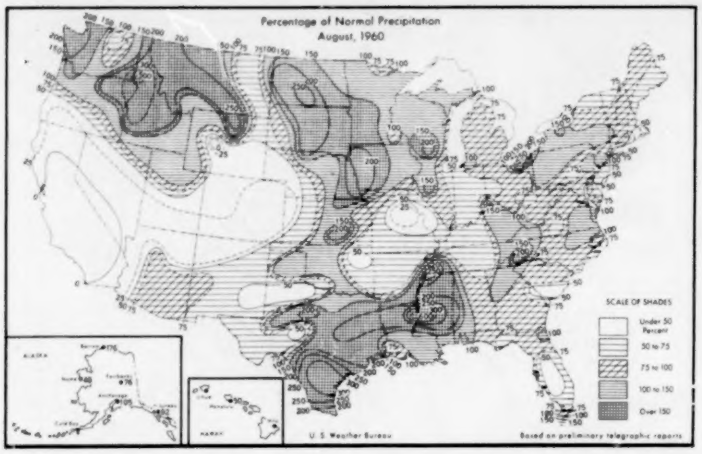


FIGURE 5.—Percentage of normal precipitation for August 1960. Above normal rainfall in the North was associated with frequent frontal activity. (From [8].)

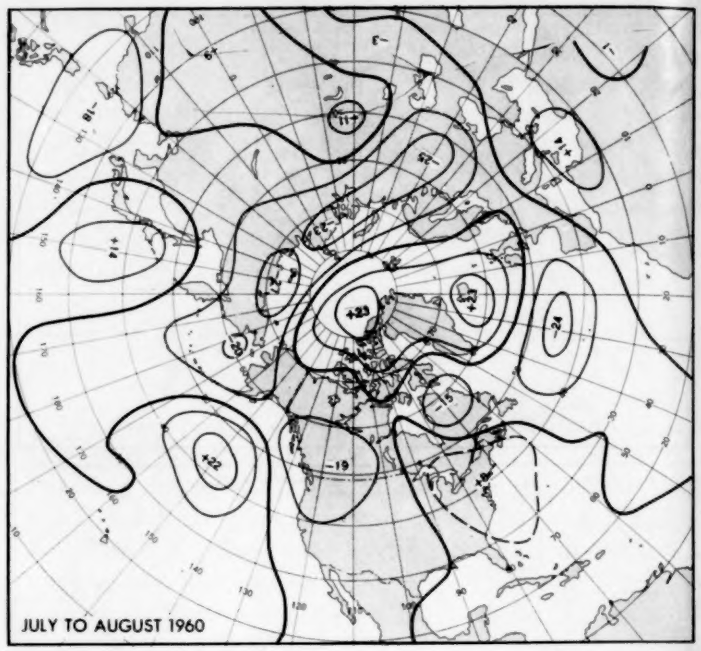


FIGURE 6.—Change in 700-mb. height departures from normal (tens of feet) from July 1960 to August 1960. The reversal of long-wave features at middle latitudes is especially apparent from Europe westward to eastern Asia.

since October 1918. Port Arthur, Tex. also had the wettest August of record with a total of 14.48 in.

4. MONTHLY MEAN 700-MB. CIRCULATION

The monthly mean circulation in the mid-troposphere (fig. 6) was dominated to a great extent by relatively strong blocking in polar latitudes. Characteristic of such widespread blocking was the expansion of the circumpolar vortex, indicated by an almost unbroken ring of negative height anomalies from 50° to 60° N. The eccentricity of blocking on the occidental side of the Pole produced southward displacement of the temperate westerlies in eastern North America, the Atlantic, and Europe. In most of Asia and the Pacific, on the other hand, the westerlies were farther north than normal.

Considering only the area from 0° to 180° in an east to west direction, the average latitude of the maximum temperate westerlies was near 45° N., the same as normal for August. Thus, the opposed displacement of the temperate westerlies, i.e., to the north in the Pacific and to the south in the Atlantic, had a canceling effect in the mean. The average speed of the temperate westerlies was 2.2 m.p.s. faster than normal, a considerable deviation to be sustained for the whole month.

In the Pacific there is normally considerable persistence in circulation features from July to August [1]. This year, however, there was little resemblance in the two months. In July the circulation was composed of a trough off Japan and another in the Gulf of Alaska [4]. Figure 7 emphasizes the changes that took place in the succeeding month. Height rises in the eastern and western Pacific and falls between resulted in the August pattern of only one trough in the Pacific.

Over North America the circulation was similarly nonpersistent as deepening in the West and filling in the East essentially reversed the pattern. There was little change in the configuration of the circulation in the Atlantic; but principal features became more intense, especially the blocking over southern Greenland.

From Europe eastward the succession of waves in the westerlies was rather chaotic, but not at all unrealistic for summertime. The relatively short wavelengths from the eastern Atlantic to eastern Asia were in distinct contrast to those in the Pacific and North America.

Of particular interest was the strength of the tropical easterlies in the Pacific. While the temperate westerlies were 2–4 m.p.s. stronger than normal in a west-to-east belt from Hokkaido to the west coast of the United States, the tropical easterlies were 2–5 m.p.s. higher than normal from 180° to the East China Sea. The unusual speed of the tropical easterlies was explicitly related to above normal heights east of Japan and intense cyclonic activity in the tropical Pacific.

5. TROPICAL STORMS

An incomplete summary of available data indicates that the frequency of tropical storms in the western Pacific in August 1960 was unprecedented [5,6]. A total of eleven storms was reported during the month, of which nine reached typhoon intensity. In 1925 and again in 1942 there were nine tropical storms in August, probably the previous record. There are several average values by several authors, but it seems that a normal frequency of tropical storms in August would lie between 4.0 and 4.5.

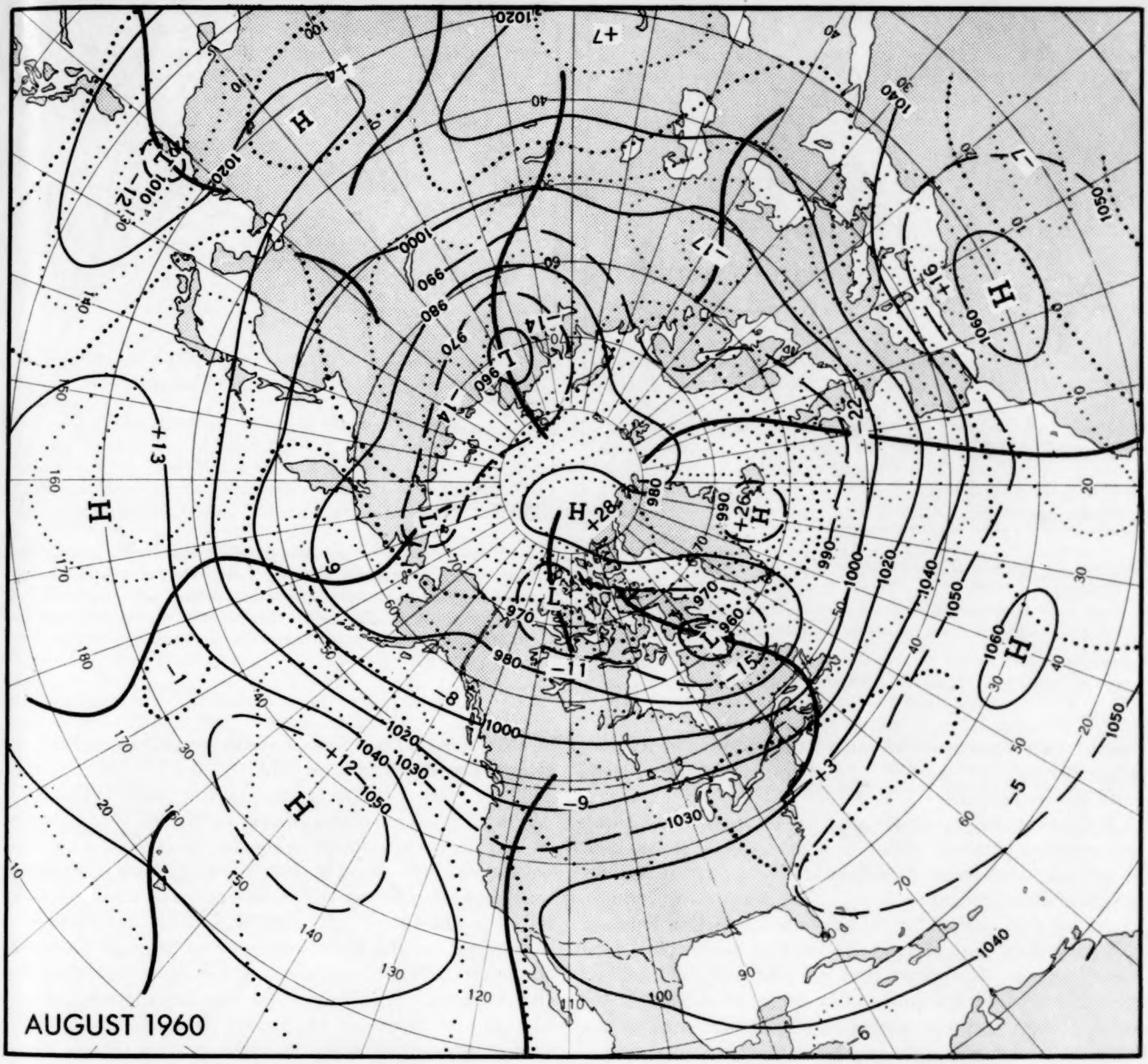


Figure 7.—Mean 700-mb. contours (solid) and height departures from normal (dotted) (both in tens of feet) for August 1960. Dominance of polar blocking is revealed by the large area of above normal heights near Greenland.

Grossly smoothed tracks taken from storm bulletins are shown in figure 8. Dashed lines are tracks of storms which did not reach typhoon intensity; solid lines are tracks of storms which were classified as typhoons at some point in their life history. Additional data on the storms shown in figure 8 are given in table 1.

The unusual tropical storm activity is well indicated on the monthly mean 700-mb. chart (fig. 6). Note especially the Low center over Taiwan and the stronger than normal southeasterly flow between this Low and the High southeast of Japan. Even though seven of the nine typhoons recurved, the monthly mean 700-mb. chart does not clearly reflect the recurvature (i.e., a strong polar trough) as emphatically as it does the locus of activity preceding recurvature. A fundamental reason is the greater speed of tropical storms after recurvature than before. A count of preliminary positions of storms which recurved indicates that between latitudes 20° and 30° N. tropical

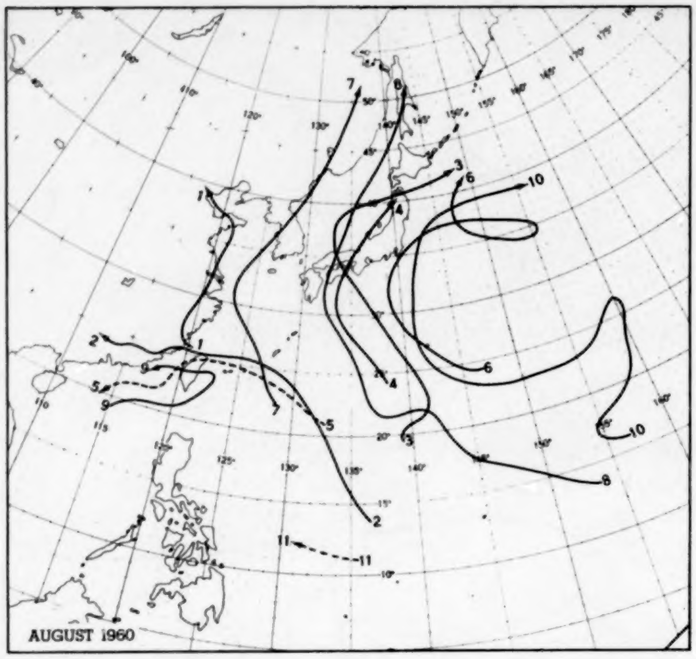


FIGURE 8.—Smoothed tracks of tropical storms in the western Pacific for August 1960. Tracks are numbered chronologically. Solid lines represent those storms which reached typhoon intensity; those which did not are shown as dashed lines. (See table 1.)

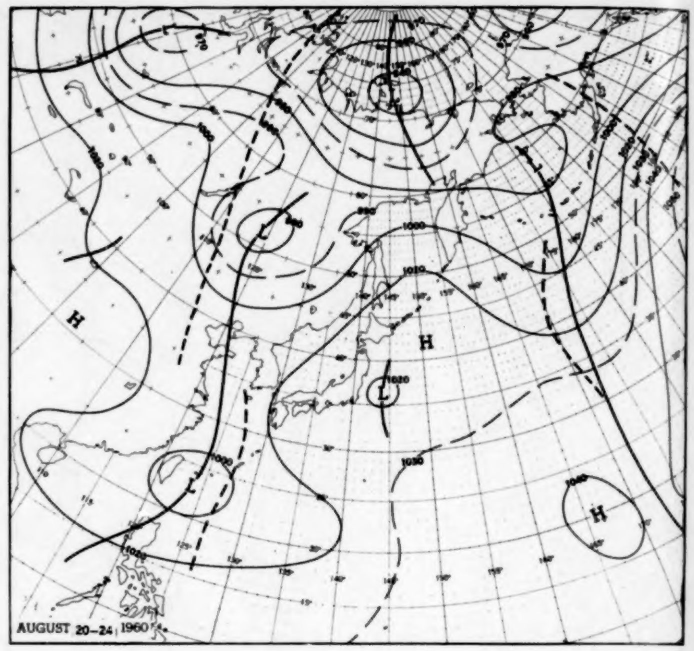


FIGURE 9.—Five-day mean 700-mb. chart for August 20–24, 1960. (Contours in tens of feet). Heavy solid lines are current trough positions; heavy dashed lines are positions of troughs for the period August 16–20, 1960. The amalgamation of polar and tropical troughs was concurrent with maximum typhoon activity.

storms were present on 28 out of the 31 days in August, while between 30° and 40° N. there were only 16 days with tropical storms.

Maximum tropical storm activity occurred in the 5-day period from August 20–24 (see table 1). On each of those five days there were four or five storms in various stages of development or decay. The 5-day mean 700-mb. chart for that period (fig. 9) shows a connection between the polar Low east of Lake Baikal and the tropical Low near Taiwan. It appears that the proximity of the polar trough increased the probability of recurvature. If the polar trough had not been progressing eastward as the easterly trough was moving westward (see heavy dashed lines), or if the polar trough had not been in existence, it is probable that tropical activity would have been inhibited instead of encouraged.

There were two hurricanes in the eastern Pacific in August. Diana was found near 15°N., 99°W. on August 16 and dissipated after striking the tip of Baja California on August 19. On the last three days of the month hurricane Estelle moved west-northwestward from an initial position near 11°N., 90°W. but did not hit land.

Opposed to the high frequency of tropical storms in the western Pacific was the single tropical disturbance in the Atlantic. Hurricane Cleo was first detected northeast of the Bahamas on August 18 and moved north-northwestward off the east coast of the United States thereafter with little damaging effect. Cleo became extratropical near Nova Scotia on August 21.

TABLE 1.—*Tropical Storms in the Western Pacific, August 1960. (Data from* [7].)

Number	Name	Dates	Maximum wind speed (kt.)
1	Shirley	1–5	125
2	Trix	4–9	135
3	Virginia	8–11	90
4	Wendy	11–12	65
5	Agnes	12–15	55
6	Bess	16–24	70
7	Carmen	16–23	75
8	Della	17–30	105
9	Elaine	20–24	80
10	Faye	22–31	135
11	Gloria	30–31	40

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